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WATER BALANCE OF LAKE NAINITAL, KUMAUN HIMALAYAS, U.P.

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NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAWAN
ROORKEE - 247 667 (INDIA)
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PREFACE

Existence of Lake Nainital has been a matter of debate in the last two decades, because it is the only source of drinking water to Nainital city, a famous tourist resort in northern India. In the tectonically active lake basin, naturally occurring landslides have generated sediments in huge amount. In addition, various anthropogenic activities viz. deforestation, construction activities and improper management of wastes have aggravated the rate of sediment delivery, endangering the life span and water availability of the lake.

As part of the project titled "Hydrological Studies of Lake Nainital" which was aimed to bring out relevant information and facts about different processes taking place in Lake Nainital, the water balance of the Lake Nainital was studied during 1994-95. The water balance of the lake has been determined using only the conventional methods. This report provides the results and detailed methodology adopted for computing or estimating different components of the water balance of the lake. In this study, apart from the relative importance of different inflow and outflow components in the hydrology of lake, an effort has been made to understand the implications of sedimentation on the lake water balance and also on the discharge of downstream springs that are sustained by the lake.

This report has been prepared by Dr. Bhishm Kumar, Sc. E and Mr. Rm. P. Nachiappan PRA with the assistance of Dr. S. P. Rai, Mr. Vinod Kumar and Mr. B. C. Dungarakoti who have worked under the Nainital Lake Project in various capacities. I hope, this report will be useful to the interested investigators, engineeers and authorities associated with lake and reservoir management.

(S. M SETH)
DIRECTOR

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ABSTRACT

The water balance of lakes provide very useful information about the availability of water in lakes at any time. In order to utilize the lake water in a planned and systematic manner and to manage the required availability of water in the lake, the knowledge of different components of water balance of lake is essential. Nainital lake is the major water source, except for the water that is directly tapped from the springs, for drinking and domestic purposes to the people living in and around the lake basin. The lake is mainly fed by precipitation water during the rainy season and inflow from the number of perrennial springs such as Pardha Dhara and subsurface inflow. Unfortunately, the study of various parameters of water balance has not been carried out in detail in the past. The lack of knowledge on few input and output parameters such as subsurface inflow, use of lake water for domestic and industrial purposes, evaporation loss and leakage from lake including the outflow through sluices gates has created uncertainty in determining the availability of water in lake. Therefore, to understand the behaviour of different inputs and outputs, the water balance study of Lake Nainital has been carried out in detail by using both conventional and isotopic techniques. The methodology followed and results obtained are presented in this report.

The rainfall data collected from the three self recording raingauges installed under the project at ATI campus, Alma and Rattan cottage sites were used in addition to the PWD ordinary raingauge data by adopting Theissen Polygon Method to estimate the average areal rainfall in the lake basin. The direct precipitation over the lake surface accounts for about 16%of the total inflow to the lake during 1995. The volume of the lake has been computed using the bathymetric data obtained using sophisticated state-of-the-art equipments by Hashimi et al.(1993). The lake area in the shallower zones have been obtained from the PWD reports. The computed volume of the lake at its full level is 8.58 Mm^3. Equations for estimating change in storage for different water levels in the shallower zones have been presented. Surface inflow to the lake has been estimated by two different techniques viz. the Lake Level Trend Analysis (LLTA) method and Soil Conservation Services - Curve Number (SCS-CN) method. The results from the two methods are comparable monsoon season. However, the inflow estimated by LLTA method is moderately higher than those estimated by SCS-CN method. The difference can be attributed to the errors in arriving at true lake level trend values during monsoon as the trend is masked by the large subsurface inflow/outflow. The surface inflow to the lake as rainfall runoff accounts for about 30% of the total inflow to the lake. The inflow to the lake through the perennial drains that are sustained by spring discharges and domestic waste accounts for nearly 15%. The sub-surface inflow estimated as residual of the solved water balance equation is nearly 39% of the total inflow components.

The surface outflow from the lake has been computed using an empirical formula for submerged rectangular sluices. The surface outflow accounts for 41% of the total outflow from the lake during 1995. One of the outflow components of the lake viz. the pumping from the lake as well as from the open well and tube wells located a couple of meters from the lake shore, accounted for nearly 32% of the total outflow. Stable isotope data were used to distiguish the differntial contribution from the lake and groundwater to the water being pumped. It has been estimted that the percentage of lake water varies from 20% during summer season to 80% during monsoon season. The open surface evaporation from the lake has been estimated using the Modified-Penman equation. The evaporation accounts for nearly 12% of the total loss. The sub-surface outflow has been estimated from the discharges interpolated from observed and historic discharges of the downstream springs located along the Balia ravine. The subsurface outflow as springs accounts for nearly 16% of the total outflow from the lake.

The water balance study indicates that the pumping pattern from the lake has a direct bearing on the water availability in the lake. This fact is clearly reflected in the relation between surface outflow and annual rainfall in the lake basin which shows a reduction in the annual surface outflow for a given amount of annual rainfall in the last 25 years. This reduction is mainly due to increased pumping. The reduction in the lake capacity due to sedimatation is very nominal. Further it has also been obserevd that the discharges of downstream springs located in the Balia ravine have declined drastically. The most probable reason for this reduction is the sedimentation that is taking place in the lake, because of which the subterranean pathways have been choked.

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1.0 INTRODUCTION

The Nainital lake is the heart of city Nainital or it will be more appropriate to say that the city came into existence only because of lake Nainital. In the past few decades, more and more construction activities have been initiated in order to cope up with the continuously increasing load of tourists. These have not only increased the possibility of land slides / instability in the area but, the forest cover has also come down considerably. All the anthropological activities have degraded the ecological environment that may lead to hydrological imbalance in case of lake Nainital. The water quality of lake has also been considerably affected. To address the related prblems the Nainital Lake Development Authority came into existence in the year 1989 which later on was renamed as Nainital Lake Region Special Area Development Authority (NLRSADA) in the year 1992.

Keeping in view the alarming situation of lake Nainital as predicted on the basis of investigations carried out by earlier investigators, a project entitled 'Hydrological studies of Lake Nainital, District Nainital, UttarPradesh' was sponsored by the Department of Environment, Lucknow, Government of UttarPradesh through NLRSADA in the year 1993. This report on the study of Water balance of Lake Nainital is based on the investigations carried out under the project.

2.0 STUDY AREA

Lake Nainital is one among a group of lakes occurring in the southern fringe of the Kumaun Lesser Himalayas (Fig. 1). The maximum length of the lake is 1.4 km, maximum width 0.45 km, maximum depth 27.3 m and mean depth 18.52 m. The lake is subdivided into two sub-basins by 100 m wide transverse underwater ridge, 7 to 20 m below the lake surface. The volume of the lake is 8.58 Mm^3. The average annual rainfall in the basin is 248.8 cm. The area of the lake basin is 4.7 km^2 out of which the surface area of lake is 0.46 Km^2 and that of Sukhatal sub-basin is 0.75 km^2. Therefore, the exclusive catchment area of Lake Nainital is 3.49 km^2. The landuse pattern of the entire lake basin is 48.4% forest, 18.3% barren, 19.3% built land and 10.4% water bodies.

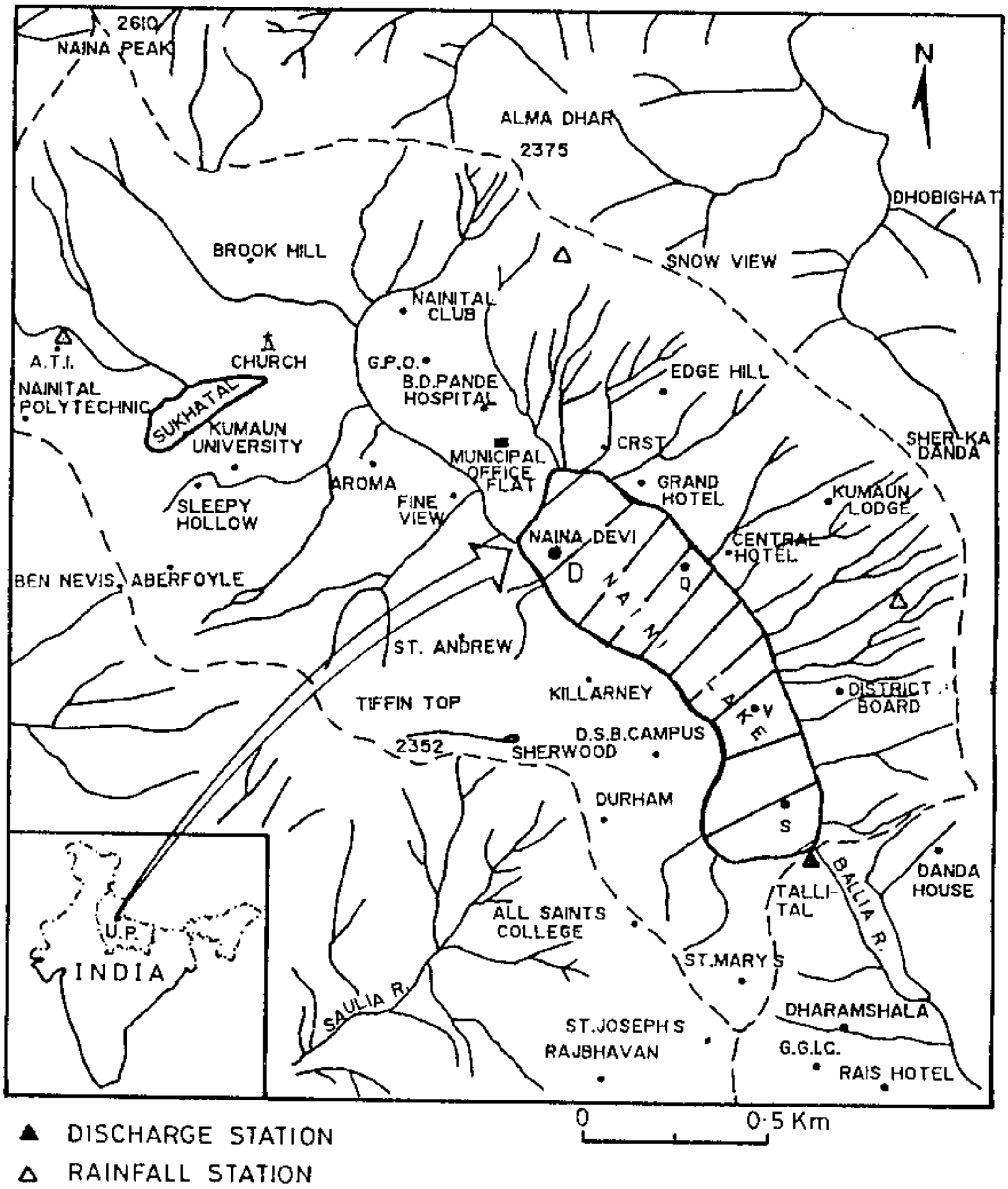


Fig. 1. Location map of Lake Nainital showing the sounding cross sections of UPPWD and the sediment core sites Q, S, V and D.

2.1 Geology and Geomorphology

The geology of the area has been well studied by many investigators. The notable works are of Middlemiss(1890), Auden(1942) and Valdiya(1988). Valdiya(1988) has given a detailed geological map of Nainital and its environs (Figure 2). The lake basin is made completely of folded and faulted rocks of Krol and Tal formations which are ascribed to Cambrian age. The lake catchment is diagonally cut by the Naini fault or the Lake Fault, as called by some geologists. The chief rock types are calcareous slates, ferruginous shales, argillaceous limestone, dolomite and dolomitic sandstones. The rotational movement along Naini fault has been the causative factor for the origin of Lake Nainital (Valdiya, 1988). The synclinal structure at Sher-ka-danda is transversed by a number of fractures tending NE-SW. The Nainital fault and these associated fractures have caused shearing and shattering of the rocks responsible for hillslope instability. Almost half the areal extent of the lake basin is covered with debris generated by mass-movements in past.

3.0 WATER BALANCE

The water balance of lakes provide very useful information about the availability of water in lakes at any time. In order to utilize the lake water in a planned and systematic manner and to manage the required availability of water in the lake, the knowledge of different components of water balance of lake is essential.

Nainital lake is the major water source, except for the water that is directly tapped from the springs, for drinking and domestic purposes to the people living in and around the lake basin. The lake is mainly fed by precipitation water during the rainy season and inflow from the number of perrennial springs such as Pardha Dhara and subsurface inflow. Unfortunately, the study of various parameters of water balance has not been carried out in detail in the past. The lack of knowledge on few input and output parameters such as subsurface inflow, use of lake water for domestic and industrial purposes, evaporation loss and leakage from lake including the outflow through sluices gates has created uncertainty in determining the availability of water in lake. Therefore, to understand the behaviour of different inputs and outputs, the water balance study of Lake Nainital has been carried out

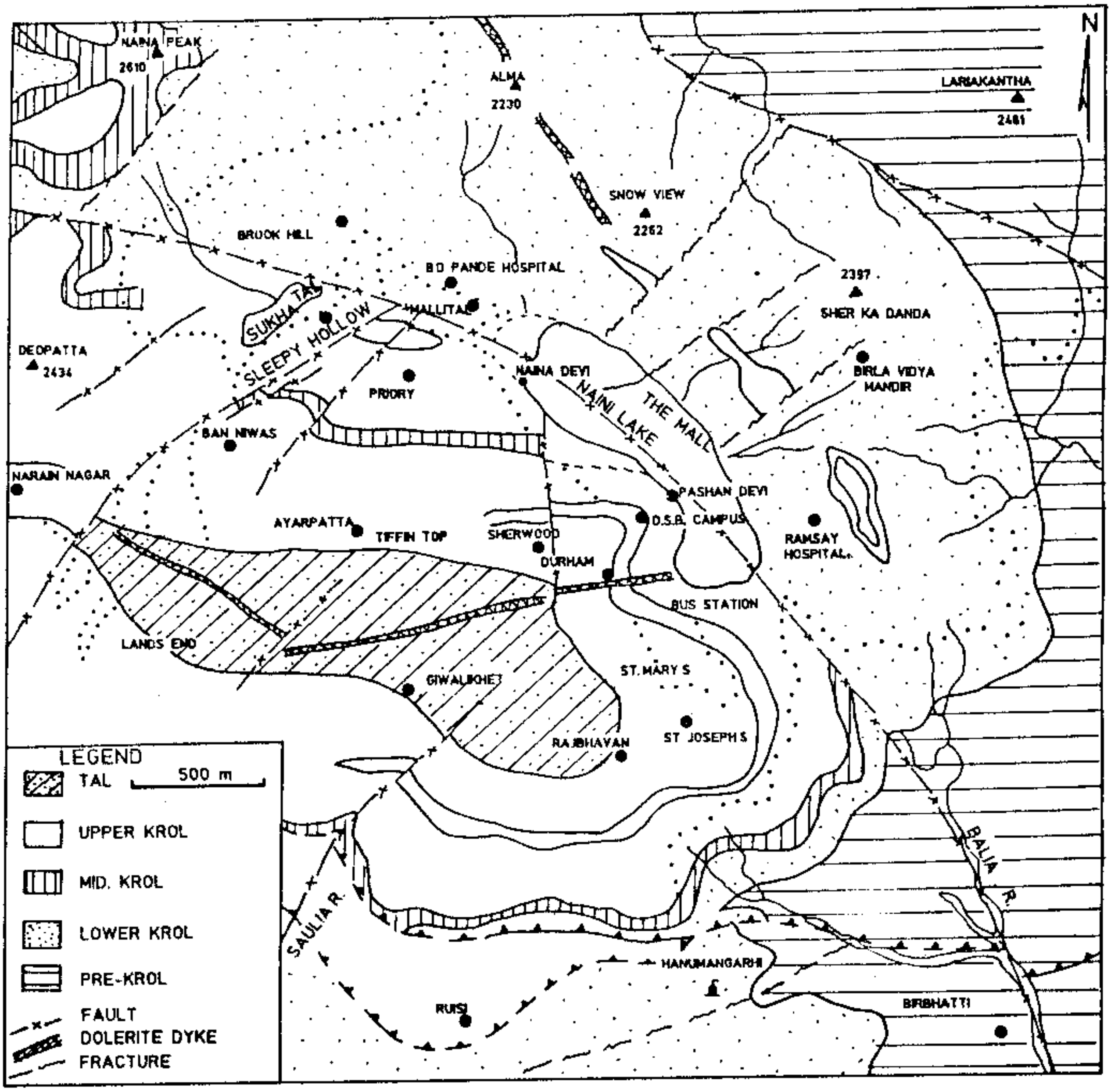


Fig. 2. Geological map of the Nainital Lake Basin showing its much faulted nature (After Valdiya, 1988).

in detail by using both conventional and isotopic techniques. The methodology followed and results obtained are summarised in the following sections.

3.1 Previous Work

No serious attempts have been made earlier to compute the water balance of Nainital Lake. During the British period, more emphasis was given to hillslope instability and accordingly a hillslide committee, was constituted which met from time to time to analyse the hill slope stability and to recommend safety measures. The sluices at the Tallital end of the lake were originally installed upon the recommendations of one such committee of in 1888, and at the same time raingauges were also installed. The hillslide committee of 1907 gave instructions regarding regulation of the draining of water from the lake. The hillslide committee 1927 made recommendations to measure various hydrological parameters for computation of percentage of runoff. The committee suggested a procedure to be followed to maintain the hydrological record on daily basis.

Very few studies have been carried out in the lake catchment, that focus on some aspects of the hydrology (Sharma, 1981; Bartarya, 1988; Valdiya & Bartarya, 1989). Valdiya & Bartarya (1989) pointed out 25 to 75% decrease in spring discharge in the past 5 to 50 years in the Gaula catchment of which the Lake Nainital basin is a tiny part located in the north-western side.

3.2 Methodology

The conventional methodologies used for computing input and output components of the water balance equation are described below.

The general water balance equation may be written as

$$\Delta S = \text{Inflow} - \text{Outflow}$$

In case of lake Nainital, the inflow term includes surface inflow (S_i), subsurface inflow (SS_i), inflow through drains (D_i), and direct precipitation (P_i). The outflow term includes controlled surface outflow through sluices and surface leakage through sluice gates (S_o), free water evaporation (E_o), subsurface outflow (SS_o) and pumping by government agencies (W_o). Incorporating the above, the Eqn. 1. could be written as

$$\Delta S = S_i + SS_i + D_i + P_i - S_o - SS_o - E_o - W_o \qquad (2)$$

The estimation of each of the above parameters is presented below.

3.2.1 Precipitation

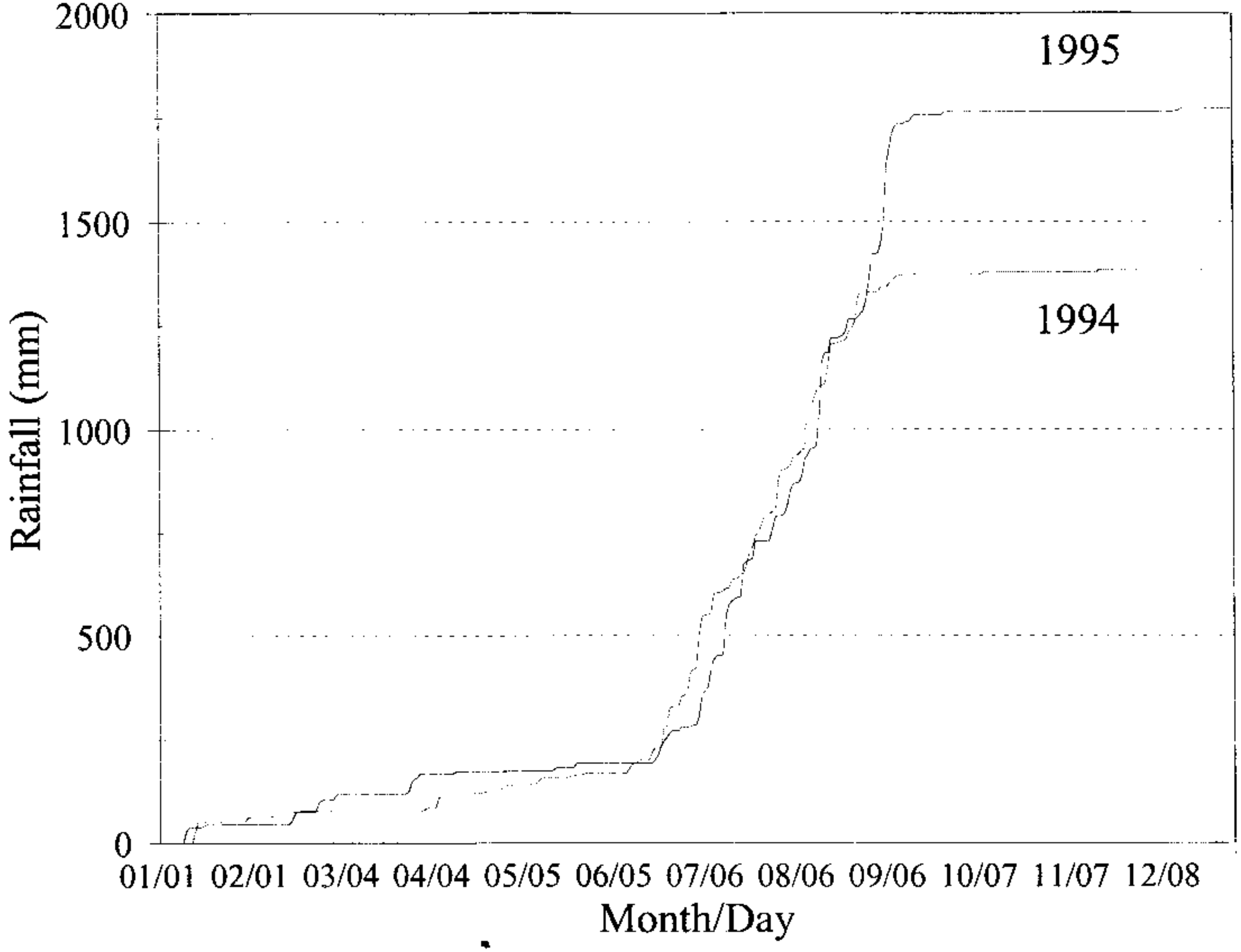
Perceptible variation of rainfall in mountainous area is a common phenomenon. Therefore to avoid the errors in measuring the precipitation in the study area, three raingauges (automatic self recording type) were installed at different locations, i. e., at the ATI campus, Alma cottage and at Rattan cottage. Besides these raingauges, the data of PWD raingauge have also been used for the present study.

By using Thiessen polygon method, the weighted factor for each raingauge has been determined (refer table). The mean daily rainfall in the basin has been computed using the rainfall data collected from the above raingauges and the respective weighting factors. The average daily rainfall data collected during the study period have been plotted (cumulative) and shown in Fig.- 3. Major part of rainfall occurs during the rainy season as non-monsoon rain is much less in comparison to the monsoon rains.

Weighting factors of different raingauge stations established in Lake Nainital Basin.

Sl. No.	Rain Gauge station	Weighting factor
1.	Alma Cottage	0.16
2.	ATI Campus	0.45
3.	PWD Site	0.14
4.	Rattan Cottage	0.25

Fig. 3 Cumulative rainfall during 1994 and 1995



3.2.2 Lake volume

Information on the lake volume is a basic requirement for any study pertaining to a lake. Computation of the lake volume using depth contours can be made by several methods (Chow, 1964).

i) Volume of lake may be determined by measuring the area enclosed by the depth contours (the location coordinates plotted against depth) and the area under the curve so obtained may be planimetered or otherwise measured.

ii) In another method, the area enclosed by successive pairs of depth contours is averaged out and multiplied by the contour interval to yield a series of volume elements which are then summed using the following relation;

$$V_{A_1A_2} = \frac{h}{3} * (A_1 + A_2 + \sqrt{A_1A_2}) \qquad (1)$$

where, h is the contour interval, A_1 is the area enclosed by the upper contour and A_2 is that enclosed by the lower contour.

Summation of the results of repeated successive applications of above equation will yield the lake volume.

3.2.2.1 Calculation of volume of Nainital lake

Bathymetric survey of Nainital lake has been carried out by several investigators using conventional (manual) sounding methods (Holland, 1895; Purohit, 1981; Rawat, 1987). Bathymetric survey carried out by Hashimi et al. (1993) using sophisticated state-of-the-art equipment has resulted in gaining bathymetric data-base of crucial import, both for tectonic interpretation and future comparison & studies. The survey was carried out in November, 1989 by using a highly sensitive echo-sounder, sub-bottom profiler and side-scan sonar and Motorala Miniranger III. Hashimi et al.(1993) presented detailed bathymetric contour (1 meter interval) of Nainital lake floor which has been used in the present study to calculate the volume of Lake Nainital. The measurement of area of each contour was carried out by using a digital planimeter. The contours for the shallower depth zone (upto 4 m) were not readable from the map of Hashimi et al. (1993). Therefore, the calculation of area was worked out with the help of map preesented by Hashimi and others, from 4 m to 27 m depth only. For the calculation of area from surface to 4 m depth, the data reported by United Province PWD (Byrnes, 1929) has been used. Byrnes (1929) has reported the contouring of lake at the interval of 1 foot, from maximum lake level (surface) upto the depth of 12 ft. This data was further interpolated to determine the depth contours in the shallow zone. Thus, the complete area and then the volume of lake, have been computed and are presented in Table- 1 and 2. The variation of lake area and volume with respect to depth have been shown in Figures- 4 & 5.

3.2.2.2 Change in storage

As a natural process, the lake level changes with respect to time. However, the change in the water level in 24 hours (a day) or in a month or in a year indicates the change in storage of the lake. With the daily observations of lake gauge, the increasing or decreasing trend of the lake storage can be studied with time which can be used to understand the various processes going on with the lake and the availability of lake water at different times quantitatively. Since the installation of sluices in 1888, the lake level is being monitored by UP PWD which is used to regulate the sluice openings.

In 1994, two water level recorders were installed under the present study at north and south sides of the lake including a staff gauge (installed in 1995) for manual monitoring of the daily lake levels. For computation of change in storage, these lake levels were analysed to determine the trend of water level, i. e., increasing or decreasing with time. The variation of daily water level for each month during the year 1994 have been plotted and shown in Fig.-6(a) and 6(b) while the variation of lake stage with rainfall have been shown in Fig.-7(a) and 7(b) for the years 1994 and 1995 respectively. The abrupt decrease in water level indicates the draining of water through sluice gates to regulate the water level in lake.

Table- 1: Lake area at different depth intervals and layer-wise volume for the whole lak

Depth (m)		Area (m^2)	Volume (m^3)
From	To	Upper Layer	
+0.53	0	463365	244852
0	1	459730	456442
1	2	451721	445786
2	3	441625	440263
3	4	439340	438196
4	5	437052	435908
5	6	434765	433621
6	7	432478	431335
7	8	430192	427015
8	9	423846	418739
9	10	413653	407967
10	11	402307	393040
11	12	383846	374868
12	13	365961	357466
13	14	349038	341704
14	15	334423	327959
15	16	321538	312650
16	17	303846	297541
17	18	291280	280378
18	19	269615	257771
19	20	245000	228752
20	21	211346	200165
21	22	186376	180226
22	23	169230	161404
23	24	147115	130994
24	25	112307	87332
25	26	67307	53487
26	27	40769	15713
Greater than 27		769	133
Total Volume (0 = 3.28 m in PWD Gauge i.e. DAT level on 22.11.1989)			8,581,714

Table- 2: Layer wise volume and cumulative volume of Lake Nainital, considering the North (Mallital) and South (Tallital) sub-basins separately.

Depth (m)	Tallital sub-basin	Cumulative Volume (m^3)	Mallital sub-basin	Cumulative Volume (m^3)	Total lake Cum. Volume (m^3)
+0.53	-	-	-	-	8,581,714
0	-	-	-	-	8,336,862
1	-	-	-	-	7,880,420
2	-	-	-	-	7,434,634
3	-	-	-	-	6,994,371
4	-	-	-	-	6,556,175
5	-	-	-	-	6,120,267
6	-	-	-	-	5,686,646
7	-	-	-	-	5,255,311
8	-	-	-	-	4,828,296
9	-	-	-	-	4,409,556
10	-	-	-	-	4,001,588
11	-	-	-	-	3,608,547
12	-	-	-	-	3,233,679
13	-	-	-	-	2,876,212
14	-	-	-	-	2,534,507
15	-	-	-	-	2,206,547
16	-	-	-	-	1,893,896
17	-	-	-	-	1,596,355
18	106,831	418,484	150,940	897,493	1,315,977
19	87,438	311,653	141,314	746,553	1,058,206
20	69,578	224,215	130,586	605,239	829,454
21	58,463	154,637	121,764	474,653	629,289
22	48,761	96,174	112,643	352,889	449,063
23	35,042	47,413	95,952	240,246	287,659
24	12,371	12,371	74,961	144,294	156,665
25	-	-	53,487	69,333	69,333
26	Nil	-	15,713	846	15,846
27	Nil	-	133	133	133

Fig. 4 Variation of surface area of lake nainital with depth

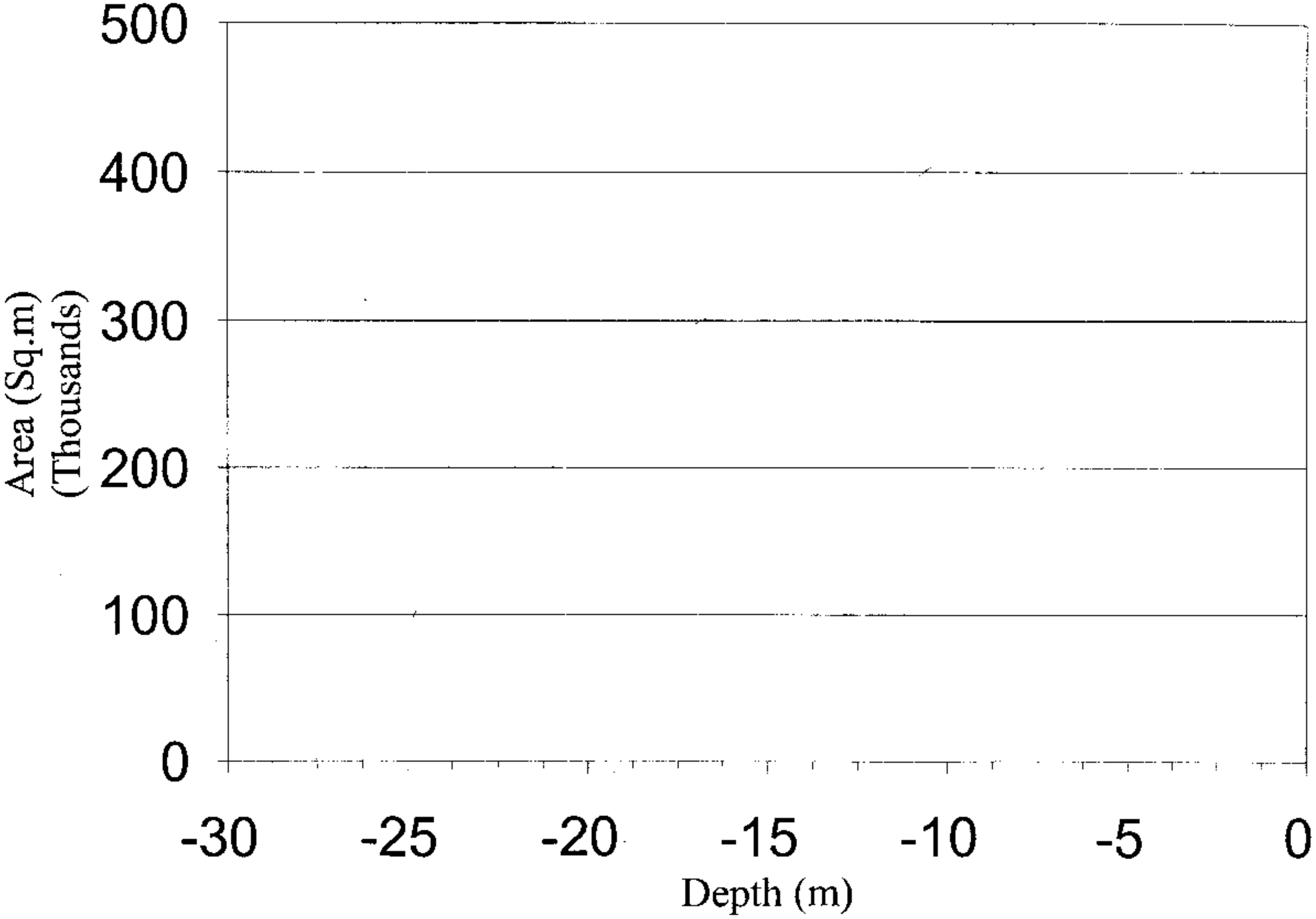


Fig. 5 Variation of volume of lake nainital with depth

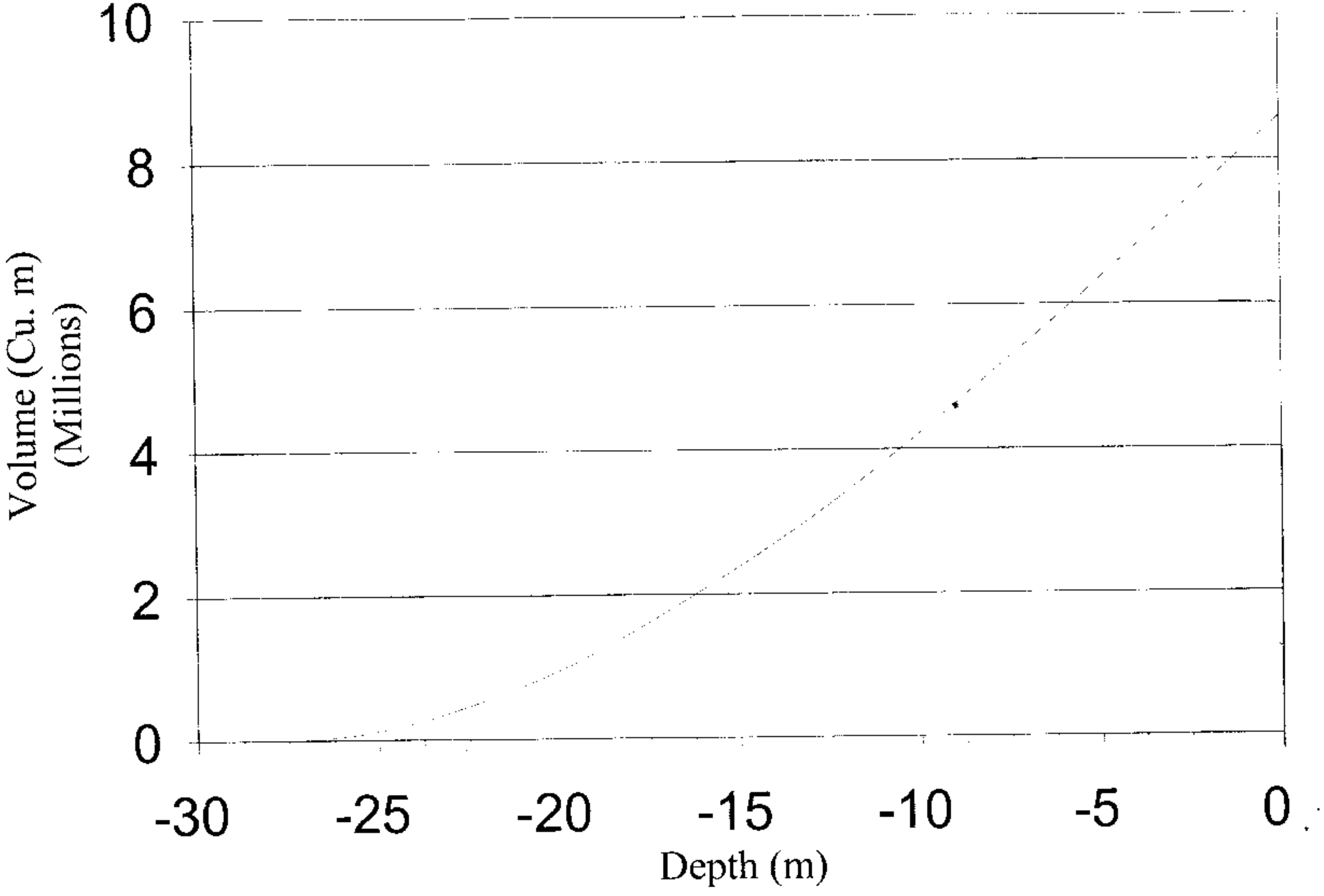


Fig. 6a: Variation of lake level with time during the year 1994.

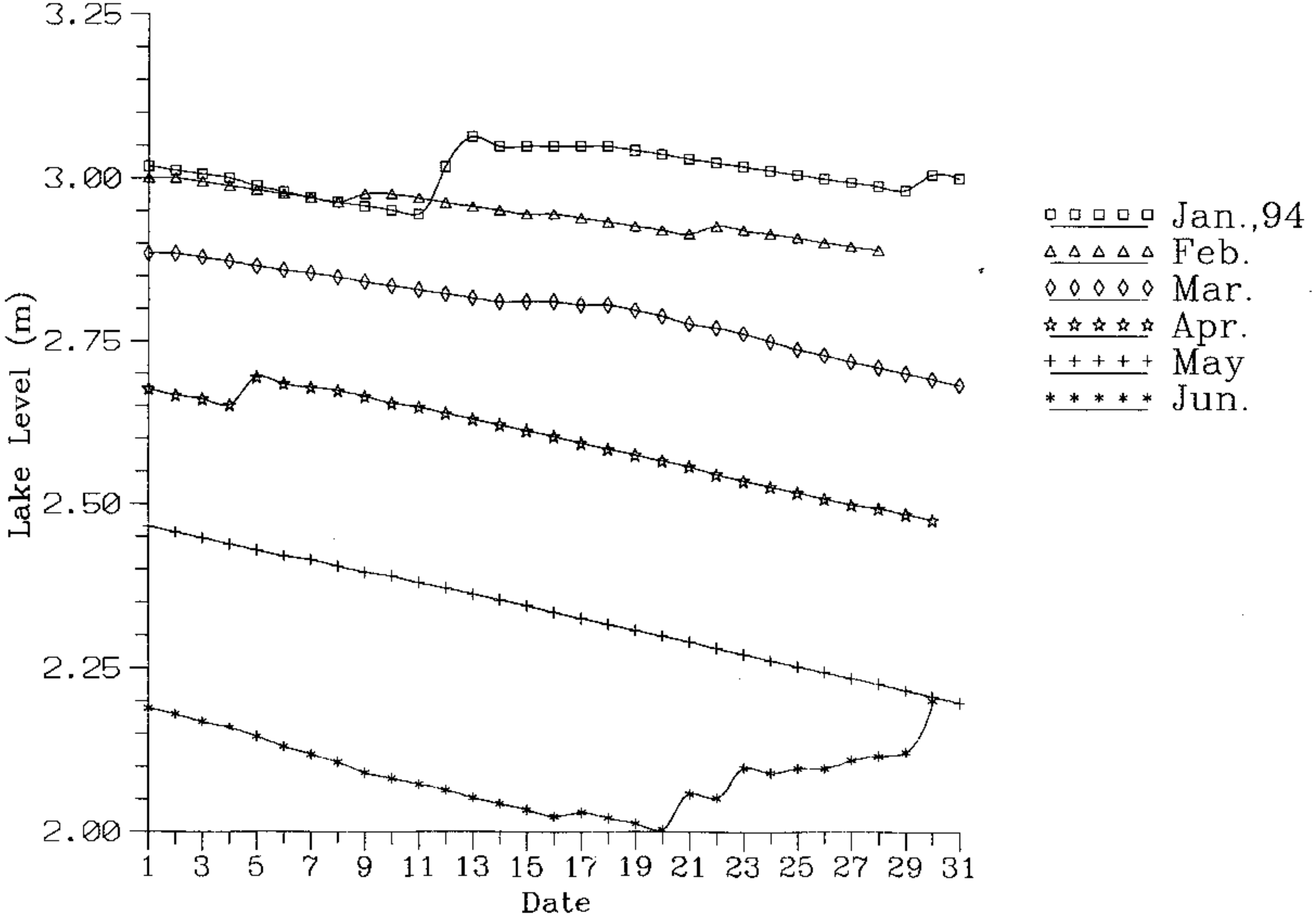
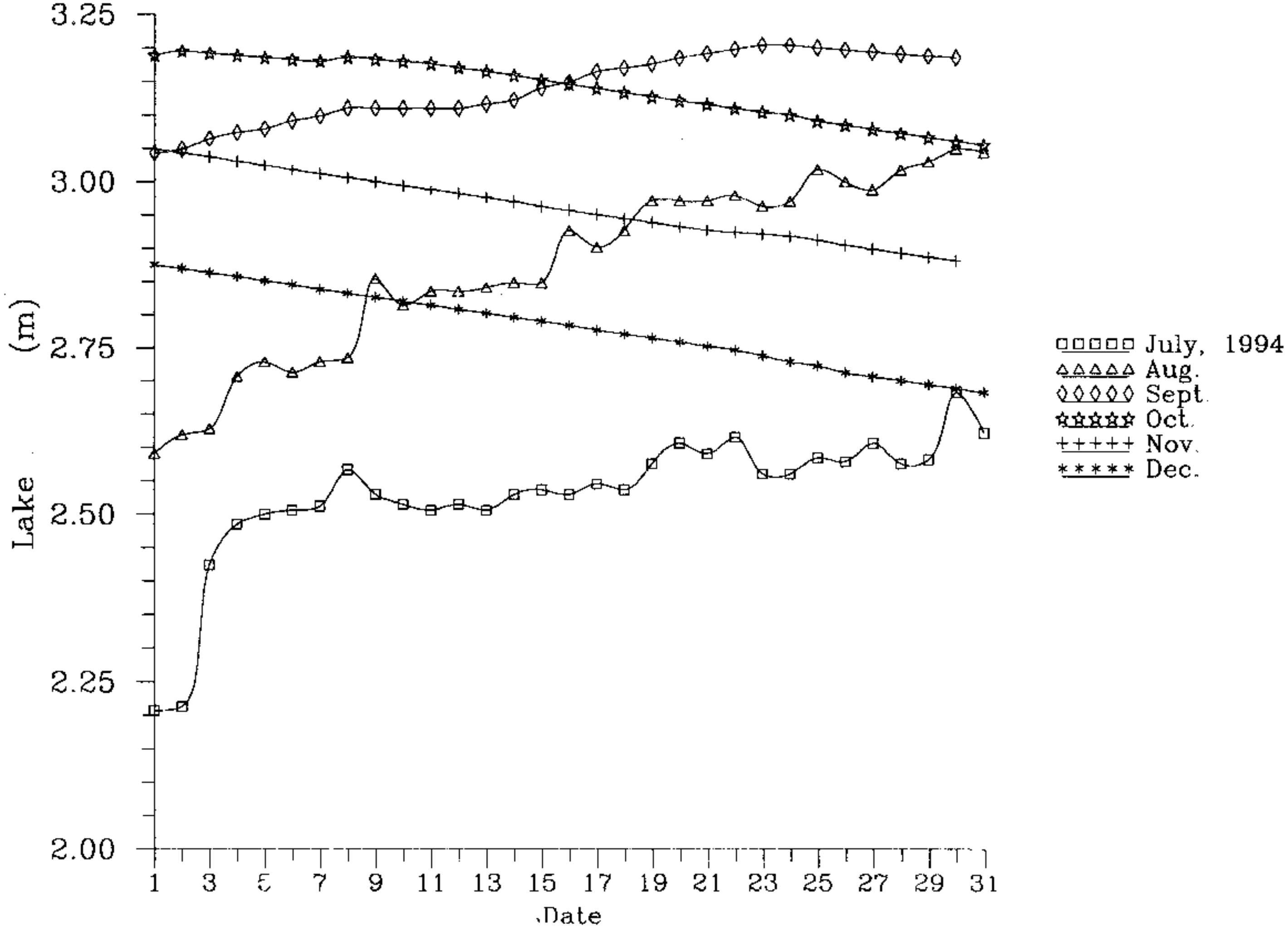


Fig. 6b: Variation of lake level with time during the year 1994.



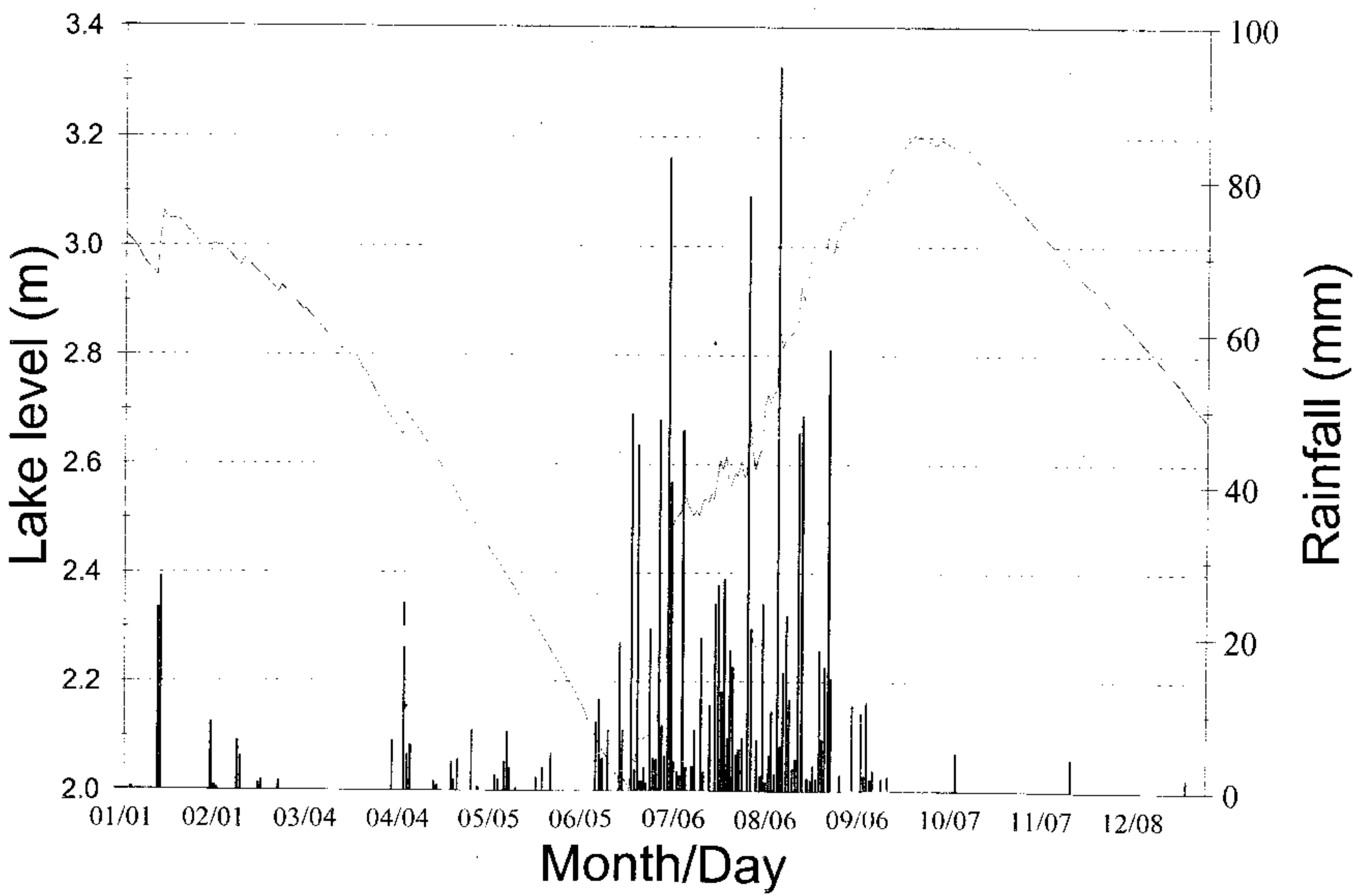
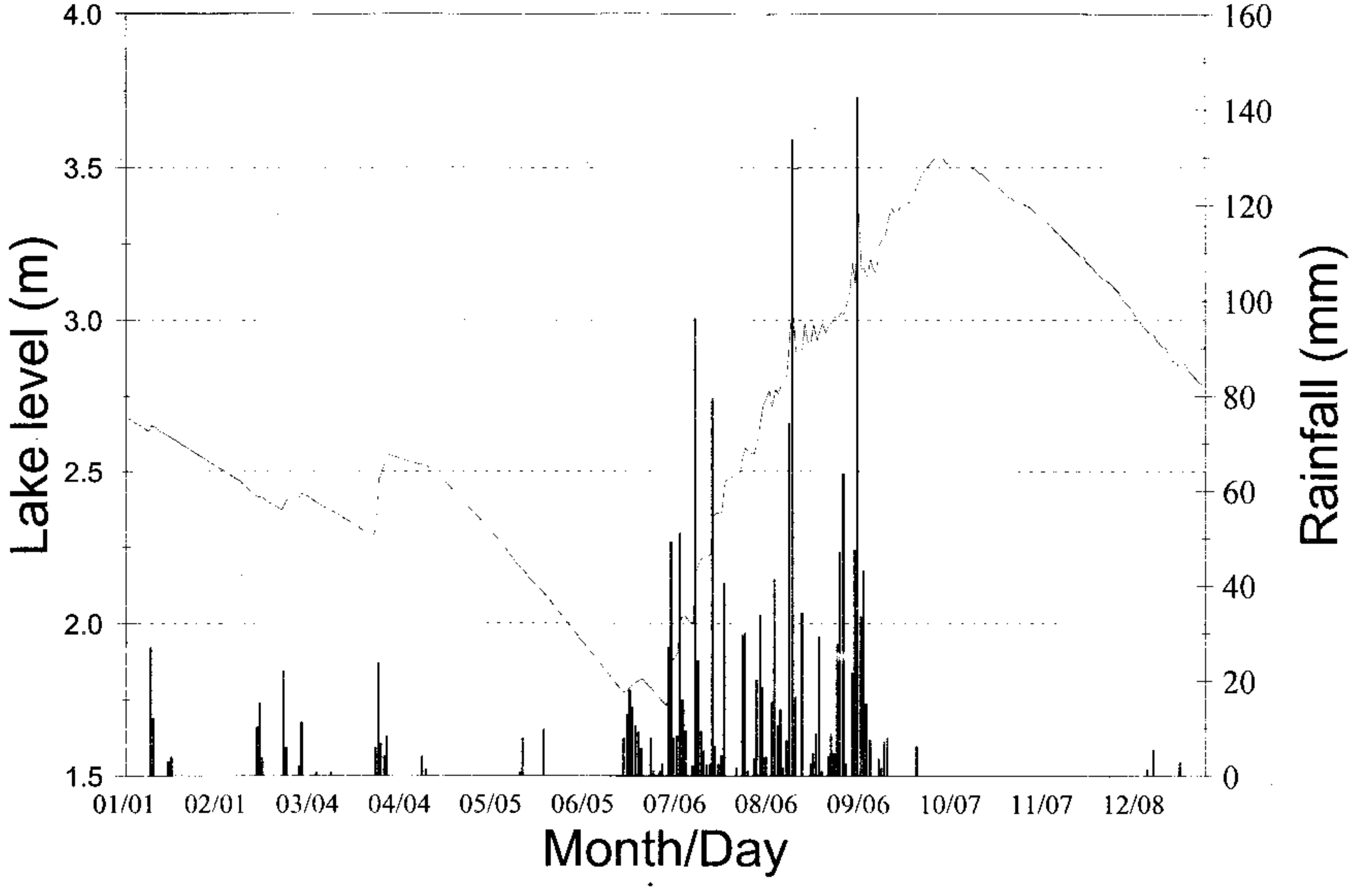


Fig. 7a Variation of lake stage of Lake Nainital along with daily rainfall during 1994

Fig. 7b Variation of lake stage of Lake Nainital along with daily rainfall during 1995



In general, the lake level follow the decreasing trend upto 2nd or 3rd week of June, depending upon the onset of monsoon. After which, the level starts increasing upto mid September. However, the fluctuations can also be easily seen in the water levels during rising trend also due to opening of the sluices to drain out the excess amount of water i. e., to regulate the lake level (the maximum lake level is 12.5 feet in the PWD gauge installed at Tallital bank). The trend of change in the lake level can be defined as the rate of change of water level with respect to input to and output from the lake at any time or time period. The drop and rise in water level indicates only less input and more output or more input and less output from a water body respectively but, in addition to this, water level trend (real time data of change in water level) can distinguish the role of any unknown process taking place. For example, surface runoff can be determined corresponding to a rainfall event if we have the information of trend of change in water level prior to the related inflow. Similarly, if surface runoff is known, the subsurface inflow or subsurface outflow can also determined with the information of trend of change in water level . The trends of change in the water level in lake have been determined at different times from the plots of water level with time and the variation of trend with rainfall are shown in figures 8(a) and 8(b) for the years 1994 and 1995 respectively.

The maximum and minimum variation of lake levels since 1900 to 1994 are shown in Table 3. The maximum change of 8.05 feet has been recorded in 1935 followed by 7.7 feet in 1955 while the minimum change of 4.3 feet in lake level was observed in 1935 & 4.5 feet in 1939 since its recording from 1931. Maximum and minimum fluctuations in the lake level mainly depend upon the annual rainfall (surface runoff) and withdrawal from the lake.

The following equations have been used to calculate the lake surface area (in m^2) from the lake level (LL) data.

For LL between 3.81 and 2.44 m $\quad \text{AREA} = 6.86 * \text{LL} + 437232$
For LL between 2.44 and 1.80 m $\quad \text{AREA} = 14.35 * \text{LL} + 418999$
For LL between 1.80 and 1.49 m $\quad \text{AREA} = 6.12 * \text{LL} + 433787$
For LL less than 1.49 m upto 0 m $\quad \text{AREA} = 2.29 * \text{LL} + 438698$

Fig. 8a Variation of weekly water level trend for 1994 and 5-year avg for the period 1991-95, along with weekly rainfall in 1994

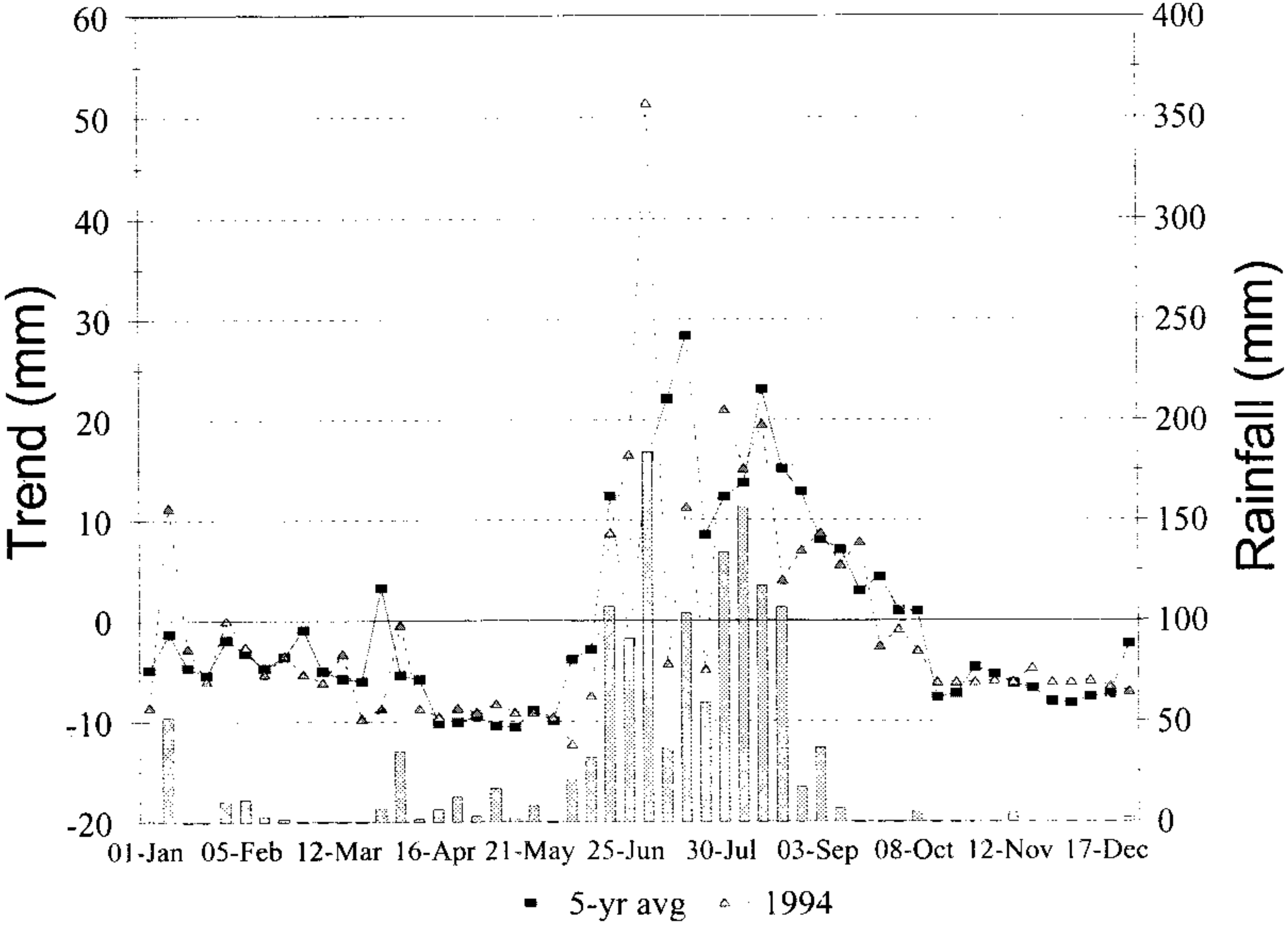


Fig. 8b Variation of weekly water level trend for 1995 and 5-year avg for the period 1991-95, along with weekly rainfall in 1995

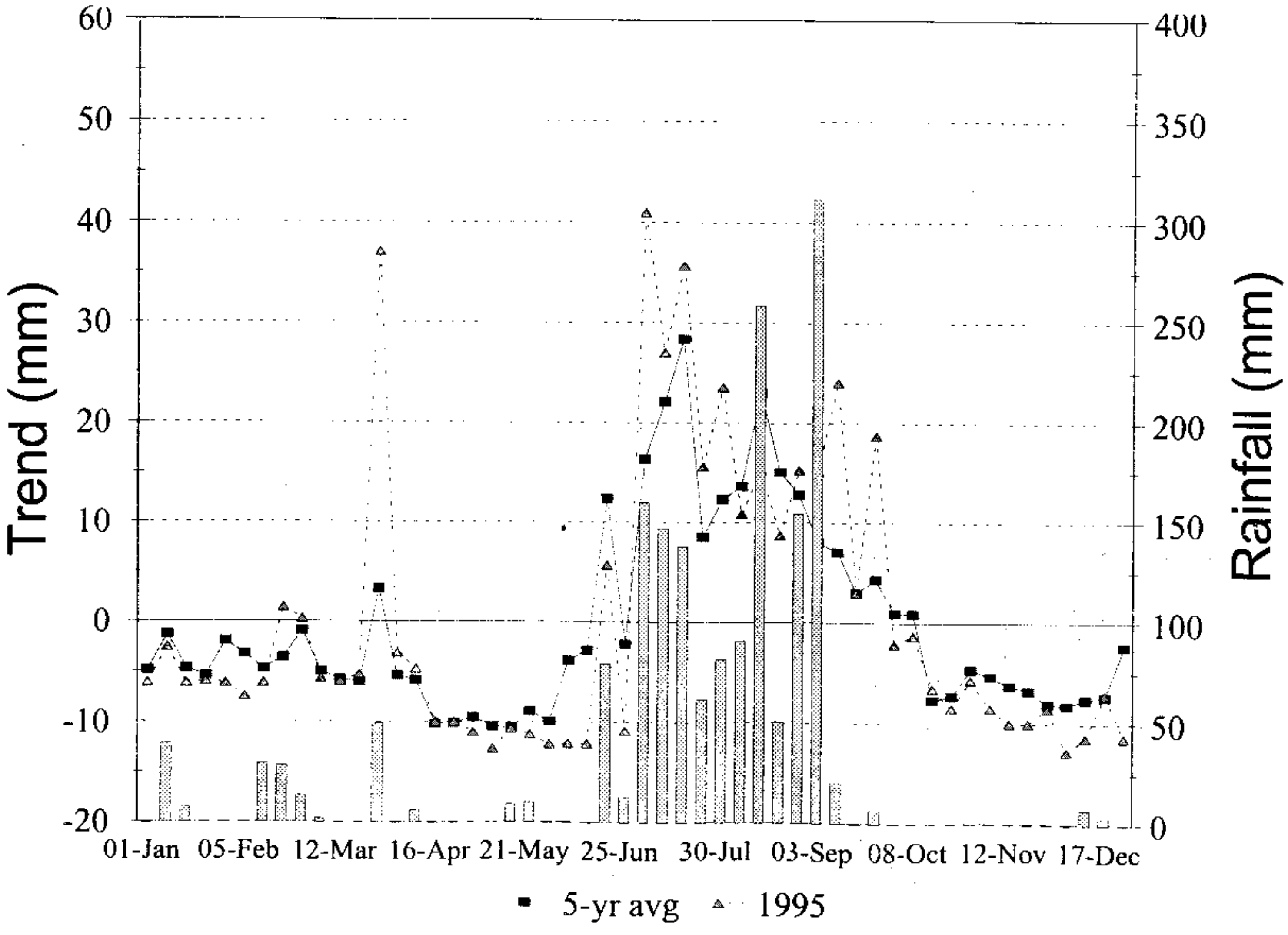


Table- 3: Minimum and maximum lake levels and fluctuations recorded from 1900 onwards

Date	Minimum Lake Level(ft)	Date	Maximum Lake Level(ft)	Fluctuation (ft)
June,1900	0.80	Sep.,1900	2.60	1.8
June,1901	1.08	Sep.,1901	3.18	2.10
June,1902	0.60	Aug.,1902	2.40	1.80
June,1903	0.65	Oct.,1903	3.15	2.50
June.1904	0.70	Oct.,1904	6.20	3.5
June,1905	0.20	Oct.,1905	3.75	3.55
June,1906	1.00	Oct.,1906	3.90	2.90
June,1908	0.10	Oct.,1908	3.60	3.50
June,1909	0.80	Oct.,1908	3.95	3.15
June,1910	1.00	Jul., 1910	5.08	4.08
June,1911	1.50	Oct.,1911	4.30	2.8
June,1912	1.25	Oct.,1912	4.35	3.1
May,1913	1.50	Oct.,1913	4.25	2.75
June,1914	1.50	Sep.,1914	4.60	3.1
June,1915	1.60	Oct.,1915	4.30	2.7
May,1916	0.90	Oct.,1916	3.20	2.30
June,1923	0.00	Oct.,1923	4.30	4.30
May,1924	1.20	Nov.,1924	4.85	6.05
....	....	....	......	.....
July, 1931	4.70	Oct.,1931	12.00	7.3
June,1932	5.00	Oct.,1932	12.20	7.2
June,1933	7.40	Oct.,1933	12.20	4.8
June,1934	5.72	Oct.,1934	11.93	6.21
June,1935	4.30	Sep.,1935	12.35	8.05
June,1936	6.40	Oct.,1936	12.40	6.00
June,1937	6.65	Oct.,1937	12.47	5.82
June,1938	7.06	Oct.,1938	12.36	5.3
June,1939	4.50	Sep.,1939	11.50	7.0
June,1940	6.10	Sep.,1940	12.50	6.4
May,1941	6.70	Sep.,1941	11.80	5.1
June,1942	6.50	Oct.,1942	12.46	5.96
June,1943	6.30	Oct.,1942	12.50	6.2
June,1944	6.78	N.A.	N.A.	N.A.
June,1946	7.60	Sep.,1946	12.45	4.85
June,1947	5.90	Oct.,1947	12.50	6.6
July,1948	5.90	Oct.,1948	12.50	6.6
June,1949	7.07	Sep.,1950	06.45	N.A.
....	....	....	......	.....
June,1955	4.73	Sep.,1955	12.43	7.7
June,1956	9.40	N.A.	N.A.	N.A
....	....	....	......	.....
June,1975	7.00	Oct.,1975	12.00	5.0
....	....	....	......	.....
N.A.	N.A.	Sep.,1989	11.35	N.A.
June,1990	8.80	Oct.,1990	11.55	2.75
June,1991	7.70	Sep.,1991	10.92	3.22
June,1992	6.40	Sep.,1992	11.61	5.21
June,1993	7.05	Sep.,1993	12.60	5.55
June,1994	6.60	Sep.,1994	10.51	3.91

where LL is the lake level in mm. The LL corresponds to the readings taken at the PWD staff gauge. 3.81 m corresponds to 12.5 ft in the gauge and 0 m corresponds to 0 ft. of the gauge, which is 1933.19 m above mean sea level. The results are then used to compute the volume between two lake levels by following the method given by Zumberge and Ayers (1964) described under section 3.2.2. The change in total storage with respect to rainfall for the years 1994 and 1995 are given in table-4.

Table 4: Change in storage (m^3) of lake Nainital during 1994 and 1995.

Months	1994	1995
Jan.	-8,010	-72,580
Feb.	-53,290	-45,640
March	-91,950	+62,010
April	-94,400	-94,640
May	-1,26,480	-1,55,550
June	+1,577	-1,10,380
July	+1,91,070	+3,62,850
Aug.	+1,92,490	+2,08,790
Sept.	+66,270	+2,31,440
Oct.	-60,310	-64,300
Nov.	-79,850	-1,29,340
Dec.	-90,580	-1,42,040
Total	-1,53,490	+50,210

3.2.3 Surface inflow

The actual surface inflow to the lake has been treated in two parts, the first being the unmonitored inflow and 24-hour response of the lake to daily rainfall and the second being the continuous inflow through the drains / channels. The latter has been separately dealt as channel inflow (D_i) which has been computed using observed values.

3.2.3.1 Lake Level Trend Analysis Method

The surface inflow to the lake can be computed from the change in storage taking into account the lake level trend (as outlined in section 3.2.2.2). This Lake Level Trend Analysis (LLTA) method is not very different from the hydrograph analyses method used in the estimation of groundwater recharge. The trend represents and accounts for different losses from the lake and also accounts for any subsurface inflow as well as subsurface outflow - as it does not vary drastically over the time interval (24-hours) that is being considered for the estimation of surface inflow. The change in water level in mm over a week's period is averaged and considered as constant for that particular week. Figures 8a and 8b show the trend during the years 1994 and 1995, respectively. Further, the five year (1991-1995) average trend has also been shown in the figures. The daily surface inflow estimated by LLTA method has been shown in Figure 9a along with that estimated by SCS-CN method (described in the following section) for the year 1995. The monthly estimates of surface inflow to the lake by both the methods for the year 1995 are shown in figure 9b. The rainfall - runoff relationship computed using the surface inflow data estimated using LLTA method for the monsoon and nonmonsoon seasons of 1995 are shown in Figures 10a and 10b.

3.2.3.2 Soil Conservation Service - Curve Number (SCS-CN) Method

The S_i has also been estimated by Soil Conservation Services - Curve Number (SCS-CN) method. The runoff curve number method has been developed by Soil Conservation Service of US Department of Agriculture. SCS-CN method is more useful for estimation of 24 hour run-off from small catchments, as it is based on 24-hr rainfall-runoff data. In this method, runoff depth is a function of total rainfall depth and an abstraction parameter called curve number (CN). The CN varies from 1 to 100 and it is a function of the following catchment characteristics:

1. Hydrologic soil type
2. Land use and treatment
3. Ground surface conditions and
4. Antecedent moisture condition (AMC).

Fig. 9a. Daily surface inflow to Lake Nainital during the year 1995, estimated by SCS-CN and LLTA methods

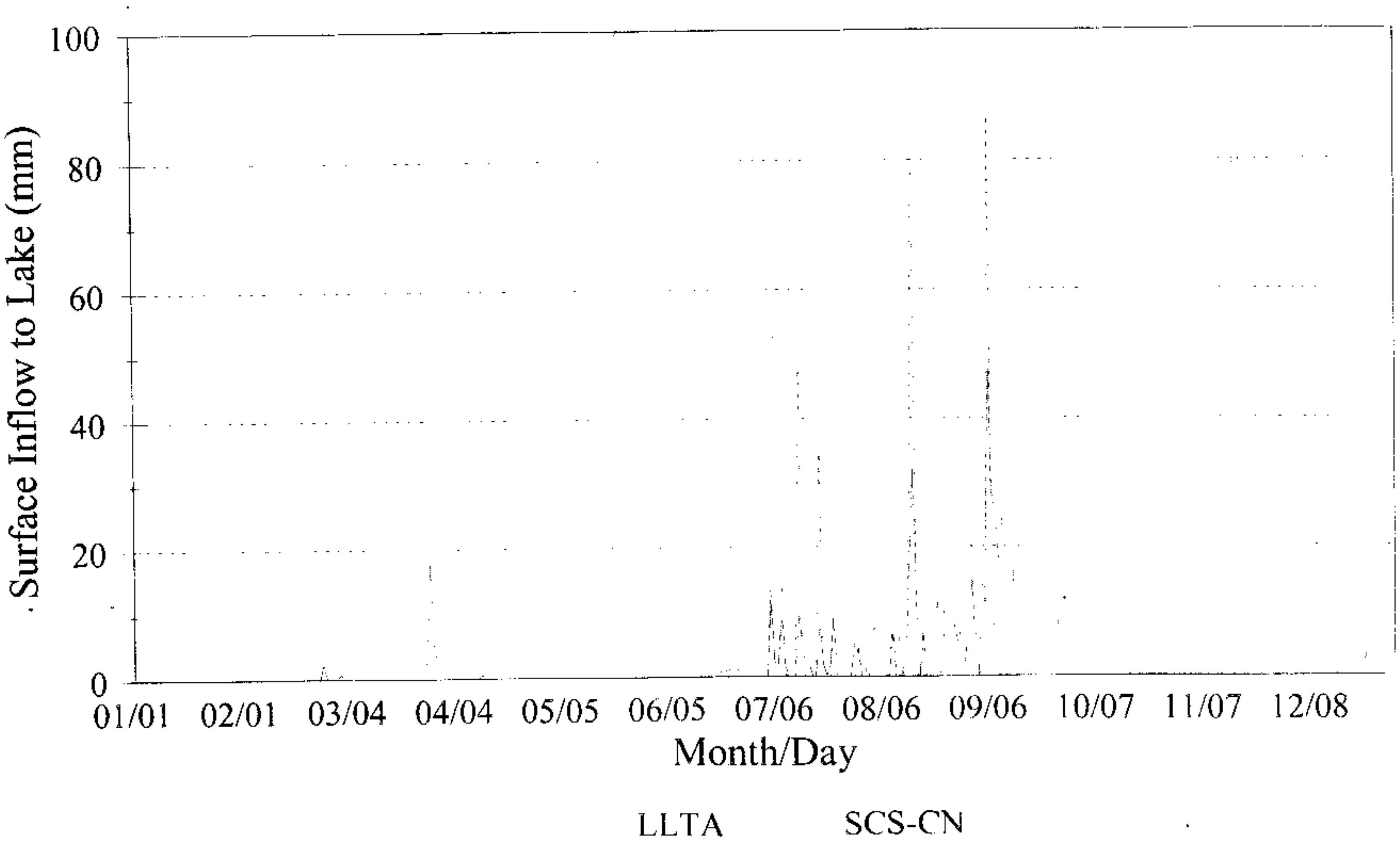


Fig. 9b. Monthly surface inflow to Lake Nainital during the year 1995, estimated by SCS-CN and LLTA methods

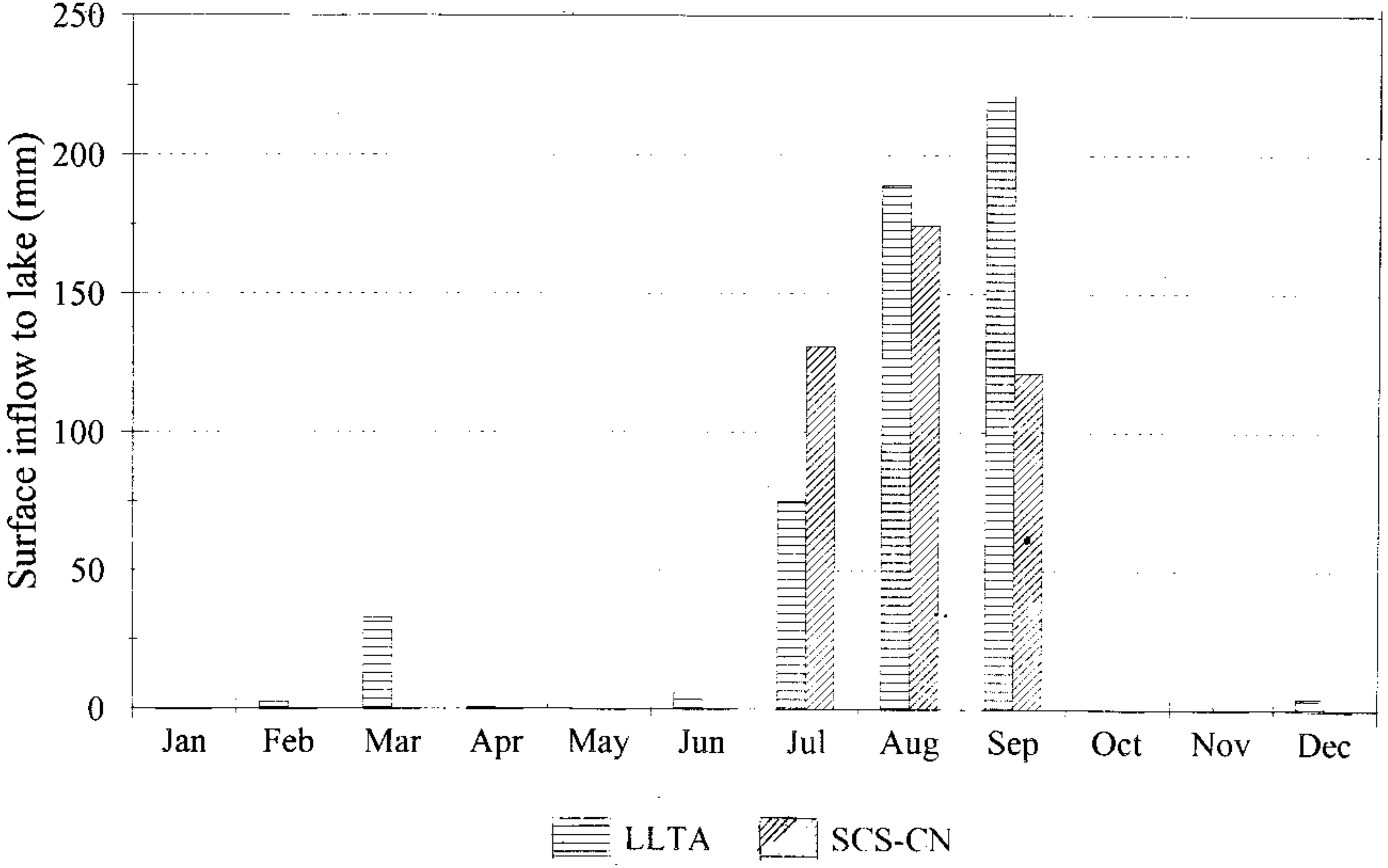


Fig. 10a Rainfall - runoff relation in Lake Nainital basin for 1995 monsoon by LLTA method

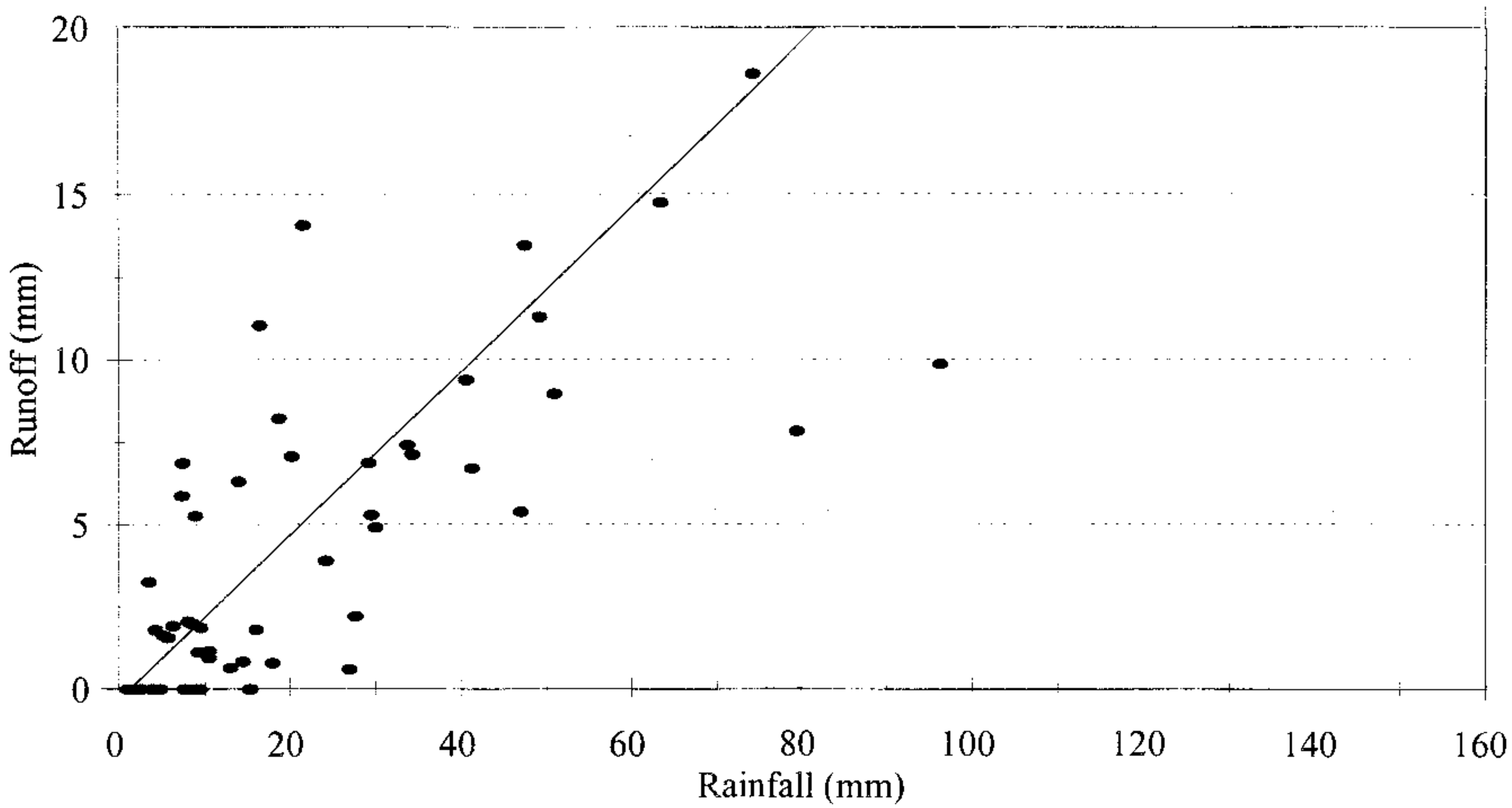
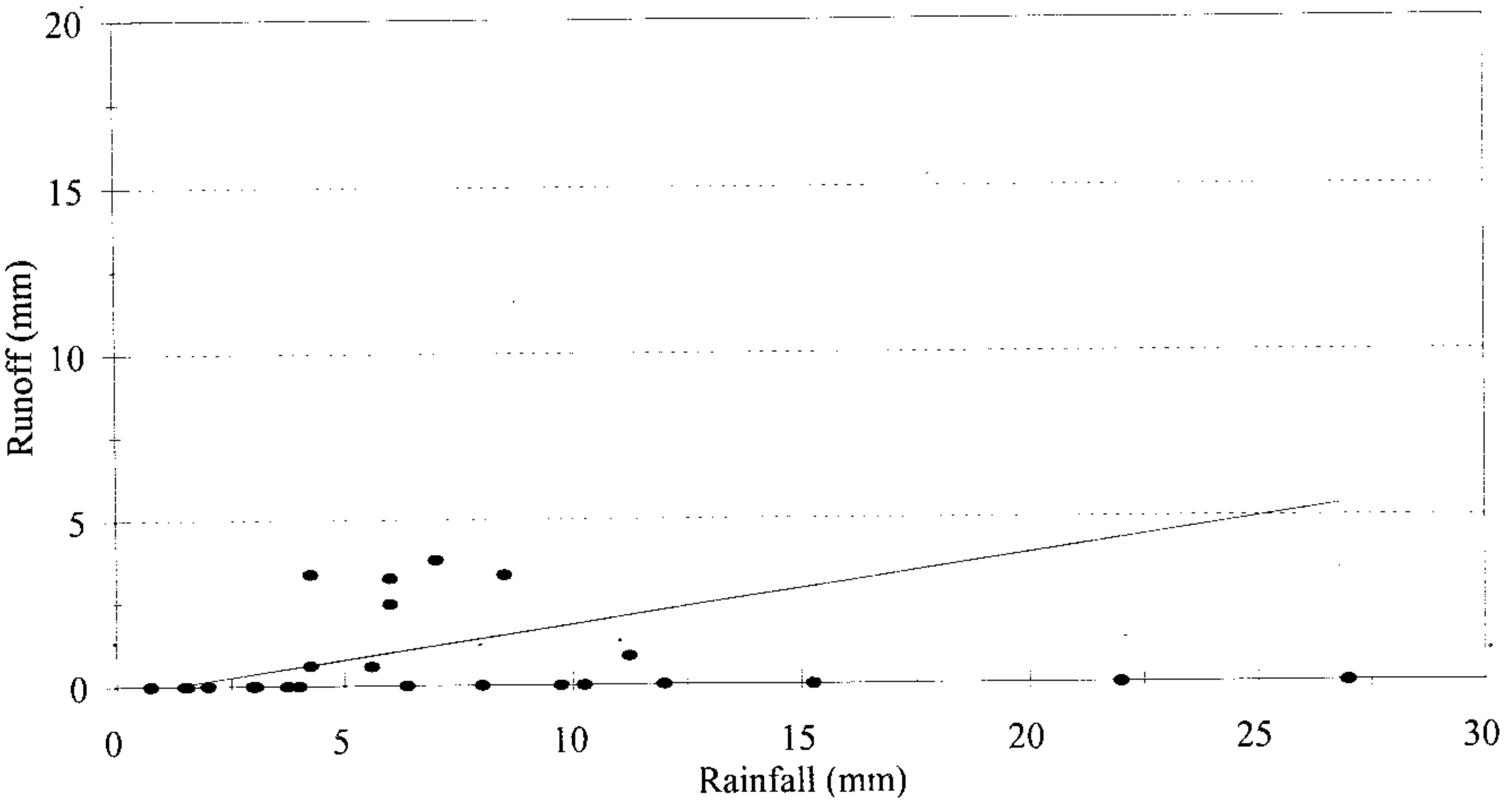


Fig. 10b Rainfall - runoff relation in Lake Nainital basin for 1995 non-monsoon by LLTA method



The basic theory of this well established and widely used method is that the runoff starts after an initial abstraction (mainly interception, infiltration and surface detention) of I_a and that the ratio between actual retention to the potential retention (S) is equal to the ratio of direct runoff (Q) to rainfall (P) minus initial abstraction. i.e.,

$$\frac{P - I_a - Q}{S} = \frac{Q}{P - I_a} \tag{2}$$

rewriting the above equation we get:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{3}$$

The quantity I_a is related to S so that, $I_a = 0.2$ S. This relation was expressed by Soil Conservation Service based on rainfall-runoff data from small experimental watersheds. Using this relationship, between initial and potential abstractions, equation (3) could be rewritten as:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{4}$$

The parameter S depends upon catchment characteristics as outlined above. The Soil Conservation Service expressed S as a function of Curve Number (CN):

$$S = \frac{1000}{CN} - 10 \tag{5}$$

CN is determined from the hydrologic soil type and antecedent moisture conditions. The hydrologic soil group are labelled as A, B, C or D. A short description of these soil groups are given in the following table:

Soil group	Soil characteristics	Minimum Infiltration rate (in./h)
A	Deep sand, deep loess and aggregated silts; High infiltration rates when wetted thoroughly.	0.30 - 0.45
B	Shallow loess and sandy loam; moderate rate of water transmission.	0.15 - 0.30
C	Clay loams, shallow sandy loam, clayey soil; Slow rate of water transmission.	0.05 - 0.15
D	Plastic clays, and soils that swell on wetting; High runoff potential and slow infiltration rates when wetted thoroughly.	<0.05

The antecedent moisture condition (AMC) refers to the soil water content at a given time. The SCS-CN method has three levels of AMC, depending on the total rainfall in the 5-day period preceding the storm, viz. AMC I, AMC II and AMC III. In AMC I, the soils are dry but not to the wilting point. AMC II reflects average conditions and AMC III has highest run-off potential with the catchment practically saturated from antecedent rainfalls. The values that are generally adopted as a measure to determine the AMC level is given in the following table:

Antecedent Moisture Condition (AMC)	Total 5-day antecedent rainfall (cm)	
	Dormant season	Growing season
I	Less than 1.3 cm	Less than 3.6 cm
II	1.3 to 2.8 cm	3.6 to 5.3 cm
III	More than 2.8 cm	More than 5.3 cm

The appropriate CN for a variety of landuses, soil treatment or farming practices along with hydrological conditions (state of vegetation growth) has been presented by SCS (1969) for AMC II. Using the land use information obtained from forest map and SPOT imagery data of 1989 and soil characteristics of the Nainital catchment, the CN has been taken from the table of curve numbers for urban areas and agricultural lands presented by SCS and as given in Ponce (1989). The following table presents the type and percent area under different Landuse, the appropriate CN and the weighted CN for AMC II for the Nainital lake catchment. The CN thus determined for AMC II has been converted to AMC I and AMC III using the relations expressed by Hawkins et al. (1985).

Land use	Ratio of area under the given Landuse to total catchment area	Hydrologic soil group	CN for AMC II
Reserved Forest	0.2352	A	30
Other Forest	0.2294	B	36
Built-up	0.4545	C	92
Barren	0.0448	C	86
Flats near lake	0.0125	A	76
Roads	0.0237		98
Composite Curve Number for AMC II			64

The surface inflow to the lake has been thus computed with the curve numbers determined on the basis of AMCs and daily rainfall data using the equations (4) and (5), with a spreadsheet software (QProWin). The estimated runoff in units of depth has been converted to units of volume using the exclusive catchment area of the Lake. Since the Sukhatal sub-catchment do not contribute to the surface inflow to the lake (there is no surface outlet from the Sukhatal catchment) it has been excluded in the estimations. The variation of different inflow components (including surface inflow using SCS-CN method) have been shown in Fig.-11 for the year 1995.

Inflow through drains [D_i]:

The Nainital catchment has a very good drainage network. There are a total of 49 public drains which after a series of interconnections join the lake through 21 outlets. Out of these 21 outlets, 14 are from the Sher-ka-danda side and 6 are from Ayarpatta side of the catchment. The remaining one, Naina Devi drain, which is the largest of all drains joins the lake from the Northeastern part. Since Naina Devi drain and Rickshaw stand drain are the perennial ones, the discharge of these drains have been monitored under the present study. The measurement was made adopting the velocity-area method. The measurements of water currents at different points in the three major drains were made using a pygmy-current meter.

3.2.4 Surface outflow

a) Discharge Through Sluices

Surface outflow from the Nainital lake occurs only in the months of rainy season because, the water level in lake is maintained at Tallital bank by the PWD, Nainital with the help of sluice gates. The lake outlet contains 5 gates, each 2.5 ft. wide and 1.25 ft. high, worked by screw type regulatory system. Each opening will have an area of 3.75 square feet. All the sluices are opened simultaneously and to the same extent. The Hill Slide Committee of 1927 formulated some regulations regarding the opening of sluices and the same are still followed, the important features of which are listed below

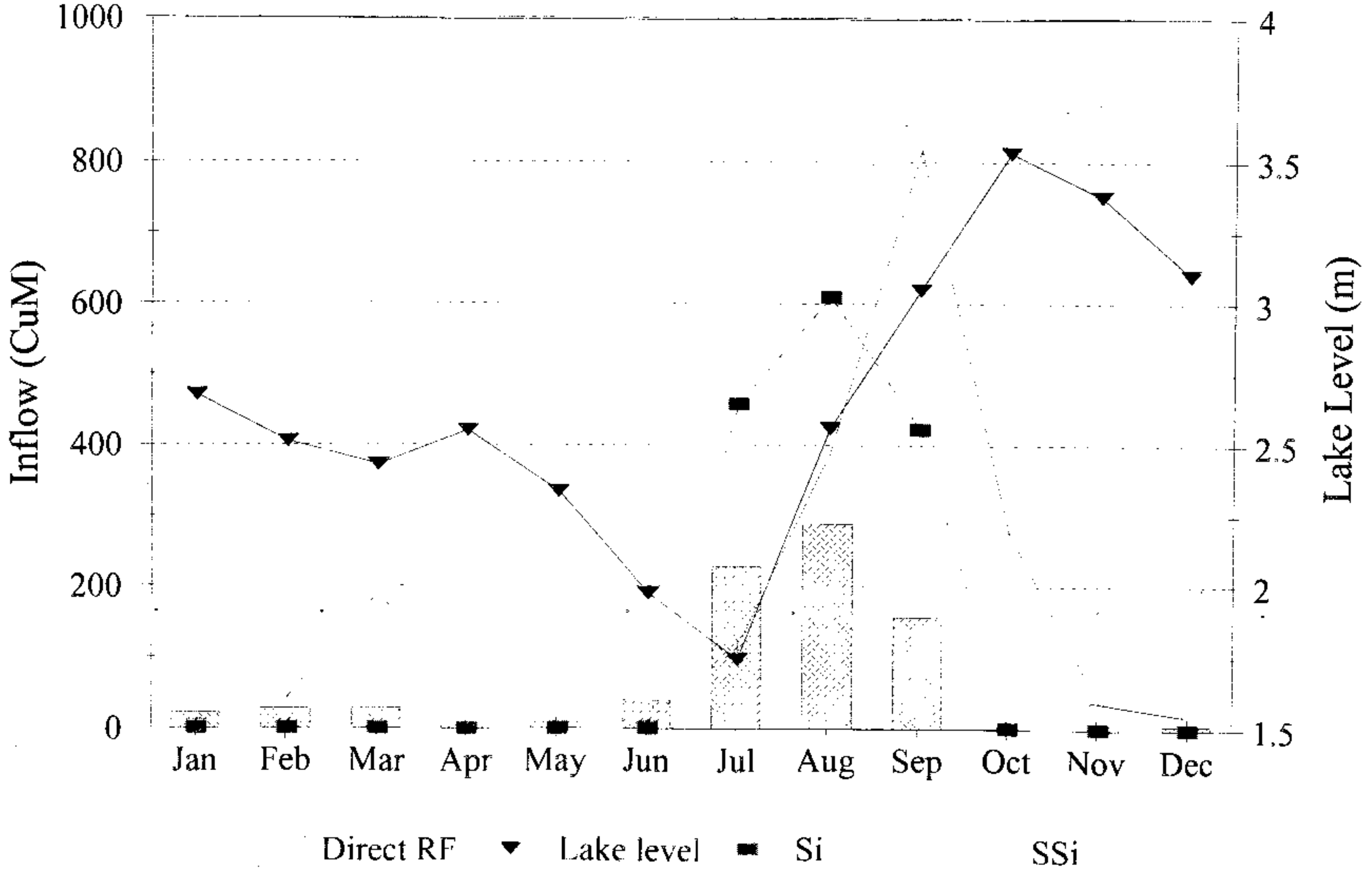
If the gauge is below 9 ft., the sluices are not to be opened more than 6", and so long as the gauge is below 9.5 ft., the sluices as a rule are not to be opened more than 12", but in the event of abnormally heavy or continuous rainfall, the District Engineer/Surveyor must use his discretion in this matter. These regulations are mainly to avoid any damage to the geotechnically sensitive Balia ravine.

The discharge through the lake outlet has been calculated by using the hydraulic equation for submerged rectangular openings. The equation for the gates installed in Lake Nainital has been given by Byrnes (1930) and the same has been adopted in the present study.

$$Q = 252780 * (h_1 - h_2) * \frac{\sqrt{h_1 + h_2}}{2} \qquad (7)$$

Where Q is the discharge in cubic feet per hour, h_1 and h_2 are the head to the bottom and top of the rectangular sluice opening in feet. The information on h_1 and h_2 have been obtained from the sluice gate operation records i.e., the time & extent of gate opening and the lake level at the time of sluice opening and closing. The records are well maintained by the UPPWD, Nainital. Further, under the present sluice operational procedures of the PWD, the sluices are never completely closed since the first day of its opening in any hydrological year until the 15th of October in that year, when the sluices are finally sealed. Leakage of lake is allowed during this period through a sluice opening of about half an inch. Therefore in the computation of the sluice discharges, the leakage has also been taken into consideration.

Fig. 11. Variation of different inflow components of Lake Nainital during 1995



b) Pumping from Nainital Lake:

The water supply from springs and lake through pipe lines was first introduced in the year 1898 in Nainital town. In those days, springs were tapped directly for domestic use by the general public, which is still continued in some places, while the steam engine plant was used to pump the water to high zones. In 1923, electric pumping stations were installed to supply water from lake to Nainital town. Presently, some deep tubewells as well as an open well, located at the banks of the lake, are being used to pump the lake water including groundwater. There are three tubewells in addtion to the eight pumping sets installed in the open well located near in the Mallital bank of the lake. Out of the tubewells, one deep tubewell, constructed recently is operated by UP Jal Nigam and the rest are operated by Jal Sansthan, Nainital. The Jal Sansthan and Jal Nigam authorities maintain the records of total pumping hours of tubewells. Therefore, the data of total pumping hours and discharge capacity of pumps & tubewells have been collected from the Jal Sansthan and Jal Nigam offices located at Nainital. One more well is operated by Army authorirties at the Mall road side bank of the lake near the Library, to meet the water requirement of military establishment at Lariakanta. The details of the of the discharge capacities of the pumps installed at lake banks are given below.

Pump No.	Location	Year of installation	Pump Capacity m^3 / hour
1	Open well	1923	69.00
2	Open well	1989	120.00
3	Open well	1985	142.20
4	Open well	1958	95.40
5	Open well	1958	72.00
6	Open well	1958	72.00
7	Open well	1958	95.40
8	Open well	1983	244.80
TW1	Tube well 1 Jal Sansthan	1991	90.00
TW2	Tube well 2 Jal Sansthan	1991	132.00
TW3	Tube well 3 Jal Nigam	1994	204.00
MW1	Military Pump House	1980	360.00

The total discharge of lake water through pumping has been calculated for the period from Jan. 1994 to Dec. 1995, on monthly basis. The withdrawal of lake water for meeting the water supply demand of city Nainital has been determined by taking 80% efficiency of the electric pumping sets as per the discussion held with the engineers concerned of Jal Sansthan. The monthly data on water pumped from the lake area during the years 94 and 95 is shown in Table-5. The monthly discharge of these pumps and tubewells varied between 2,23,580 m^3/month to 4,99,100 m^3/month during 1994-95. The quantum of water pumped varies significantly in different months depending upon the demand. During April to June, pumping is higher and during September to November it is lower (Table- 5).

Table- 5: Total discharge of water pumped (m^3) out from Lake Nainital in different months and years during the study period.

Months	1994	1995
January	2,44,470	3,72,970
February	2,43,550	3,56,250
March	2,95,500	4,09,180
April	3,34,900	4,79,270
May	4,59,290	4,99,100
June	4,69,130	4,68,240
July	4,02,760	4,40,690
August	2,68,120	3,21,450
September	2,23,580	2,42,750
October	3,18,820	2,34,330
November	3,34,170	2,95,700
December	3,40,930	3,31,990
Total	39,35,220	44,51,920

The values presented in Table - 5, are total water pumped through the wells located in the banks of the lake Nainital. However, from the stable isotope data it has been found that not all the water that is being pumped is lake water. The water drawn from the wells is a mixture of both lake water and groundwater. Based on the stable isotopic signatures of lake water and groundwater, it has been estimated that the proportion of lake water in the water that is being pumped varies from 25% during winter season (January - March), 20% during summer season (April - June), 80% during Monsoon season (July - August), and 40% during post-monsoon season (September - December). Based on these information the values of Wo have been corrected accordingly and included in water balance calculations.

3.2.5 Evaporation

The estimation of evaporation is rather complicated. Several equations for estimating evaporation from free water surfaces exist in literature. In a recent and most comprehensive article, Winter *et al* (1995) have evaluated 11 equations for the estimation of lake evaporation. Of the three types of approaches to the estimation of evaporation, viz. energy balance, mass transfer and combination (Penman type), the first one yields more reliable results, if data on all associated energy terms are available. Alternatively, if sufficient data are available, the combination methods yield better results. Based on the relative merits outlined in the literature, the Penman method (Jensen, 1974) was chosen. The equation for the estimation of evaporation is:

$$\frac{\Delta}{\gamma + \Delta} * (Q_N + G) + \frac{\gamma}{\gamma + \Delta} * 15.36 * (0.5 + 0.01 * U_2) * (e_0 + e_a) \qquad (8)$$

Where, γ and Δ are the weighting factors. Q_N is the net solar radiation. G is the advected energy which is negligible. U_2 is the wind velocity in m/s at 2m above lake surface. e_0 and e_a are the saturated vapour pressure (mb) at the water surface temperature and actual vapour pressure (mb) at air temperature, respectively.

Δ is the slope of the vapour pressure versus temperature curve and is expressed in mb/°C. The following equation can be used for the computation of Δ, which is the slope of the vapour pressure vs. temperature curve.

$$\Delta = \frac{25083}{(T + 237.3)^2} \exp\left(\frac{17.3 * T}{T + 237.3}\right) \qquad (9)$$

where T is the mean air temperature in °C.

γ, the psychrometric constant is computed using the following equation:

$$\gamma = \frac{0.61 * P}{1000} \qquad (10)$$

where P is the mean atmospheric pressure in mb. The atmospheric pressure data have been collected from UP State Observatory at Manora that is located 2 km south of the lake site, at almost a similar altitude.

Since the solar radiation data for the site was not available, the net radiation (Q_N) was computed using the following relationship:

$$Q_N = Q_S * (1-\alpha) - Q_{LN} \qquad (11)$$

where, α is the albedo (reflection coefficient), Q_S is the global solar radiation and Q_{LN} is the net long wave radiation. The α for the present study was computed by using the values presented for different amount of cloud cover (Ter-Makaryantz, 1960). The sunshine hours data collected by Uttar Pradesh State Observatory (UPSO) located about 2 km south of the lake was used to generate the cloud cover data. Rao *et al* (1971), after analysing meterological data collected from IMD Stations from all over India, proposed the following equation for the computation of Q_S.

$$Q_S = Q_A * [0.325 * COS\Phi + 0.385 * (\frac{n}{N})] \qquad (12)$$

where Φ is the latitude and n and N are actual and maximum possible sunshine hours respectively. Q_A, the extraterrestrial radiation and N for the site were computed using the Duffie Beckman equations (Allen, 1996). Q_{LN} was computed by the following equation (Shuttleworth, 1992):

$$Q_{LN} = -f\epsilon'\sigma T^4 \qquad (13)$$

where, σ is the stefan boltzmann constant, T is the absolute temperature in Kelvin, f is the adjustment factor for cloud cover, which is roughly equal to (0.1+0.9*n/N) (Singh, 1992) and ϵ' is the emissivity factor, which was computed using the Idso-Jackson equation.

e_0 can be calculated using the following equation (Linsely et al., 1975):

$$e_0 = 33.8639 * [(0.00738\ T_0 + 0.8072) - 0.000019 * |1.8\ T_0 + 48| + 0.001316] \quad (14)$$

The actual vapour pressure e_a can be computed by multiplying the relative humidity with the saturated vapour pressure at a given air temperature.

The parameters, required for the Penman equation, viz., air & water temperatures and relative humidity were measured at the lake site. Evaporation data was also collected directly from a USWB Class-A Pan installed at the lake site. The values of estimated evaporation from lake Nainital and estimated & measured parameters used for the computation of evaporation are presented in Table- 6(a) and 6(b) respectively.

Table 6(a): Monthly variations of evaporation (m^3) from Nainital Lake during different years.

Months	1994	1995
Jan.	30,380	31,740
Feb.	27,680	36,850
March	50,350	55,660
April	63,830	62,310
May	72,580	72,070
June	62,370	56,860
July	54,410	55,430
Aug.	47,030	51,090
Sept.	50,780	46,930
Oct.	47,050	45,100
Nov.	28,500	35,180
Dec.	28,980	26,020
Total	5,63,930	5,75,240

Table- 6(b): Values of measured and estimated parameters used in the estimation of evaporation from Lake Nainital by Penman Method for the year 1995. (See text for details).

1995	Atm. Press.	Sun Shine	Air Temp.	Lake Temp.	Wind Velo.	Rel. Humi.	Alpha Coeff.	Net Radn.	Lake Evap.
Units	mb	Hrs.	°C	°C	m/s	%	-	ly/day	mm
Jan	812.78	6.76	4.43	8.82	3.19	58.42	0.087	145.19	2.14
Feb	812.37	6.22	6.41	8.78	3.23	53.42	0.074	191.07	2.68
Mar	813.48	8.61	10.05	12.08	4.89	47.96	0.068	278.47	3.80
Apr	812.82	6.47	15.31	15.96	4.15	47.30	0.058	310.60	4.38
May	812.26	8.25	20.22	19.90	4.73	61.95	0.061	368.75	5.15
Jun	809.57	2.41	21.78	22.47	3.60	68.88	0.056	288.31	4.12
Jul	809.27	3.10	18.77	21.51	2.75	85.74	0.057	295.06	3.90
Aug	810.02	2.91	18.41	20.93	2.72	87.43	0.056	272.73	3.58
Sep	811.97	4.53	17.18	20.13	2.25	81.10	0.064	256.56	3.40
Oct	814.50	8.28	15.32	18.42	2.12	72.64	0.062	239.31	3.22
Nov	813.86	8.94	12.22	14.64	1.75	51.17	0.076	169.25	2.60
Dec	814.15	7.76	8.67	11.17	1.82	53.81	0.087	129.19	2.08

3.2.6 Subsurface inflow and subsurface outflow

These are most difficult parameters to be estimated or arrived at by any means, among all the components of the water balance equation as given in equation (2). Attempts have been made by researchers world-over to find a suitable method to estimate the subsurface inflow to a lake. Use of seepage meters have been reported, but with limited success. The reason for its limited application is due to logistic problems of installation of the meters and periodic retreival and replacement of the collectors. The most widely adopted method is to assign the residual values of equation (2) to the sub-surface components. Winter (1980) cautioned that this pratice will lead to adding up of the accumulated errors in other components of the water balance equation to the sub-surface terms. Another option to estimate the sub-surface inflow may be the estimation of sub-surface outflow and then deducting it from the residuals. Conventionally this may be done by identifying all possible sub-surface outflows (springs) and to measure their discharge. Alternatively, stable isotope mass balance method could be adopted.

Under the aegis of the then UPPWD, the average monthly discharge of the downstream springs were monitored and were included in the water account statement prepared by the PWD. The main objective of the water accounting exercise was to judge the efficency of the surface drainage systems to avoid land-slides. Although there were certain flaws in the accounting system leading to under or over estimation surface run-off (during certain years the accounted water far exceeded the total annual rainfall in the basin) the spring discharge data are very useful in arriving at an approximate estimate of sub-surface outflow. The monthly discharge data of different springs located downstream of the lake are available with the UPPWD for selected period and the same have been collected. The period for which the discharge data are available (1931, 1947-52, 1966-79) is small. However, the data are very useful. Out of the nine springs such as, Tallital spring, Fairy Hall Spring, Old Reserve Police Lines (Rais Hotel), Mota Pani (Siahidhara), Katarpani, Cantonement drain etc., Rais Hotel and Sipahidhara alone account for 90 - 94% of the total annual spring discharge. Some of the springs for which discharge were measured have since gone dry, and the discharge of major springs such as sipahidhara has decreased considerably. The aggregate monthly discharge of all springs and also that of sipahidhara have been presented in Table 7. The discharge of sipahidhara spring only was monitored during 1995. Based on the ratio of discharge of sipahidhara spring to the total discharge of all springs using the available historic data, the total discharge of all the springs for the year 1995 has been computed and has been presented in Table 7. Considering the computed spring discharge as well as the pumping through the wells as sub-surface outflow (SS_o) the SS_i has been estimated by solving equation 2 and the results are presented in Table 10a and 10b.

One of the major sub-surface inflow source to the Lake Nainital is the contribution from the Sukhatal sub-catchment (0.75 km^2) through the Naini fault (also called as Lake fault). Since this fault extends beyond the lake basin (upstream direction), it is possible that more water that percolates into the ground outside the catchment area in the vicinity of the fault zone finds its way to the Lake Nainital through the sub-terranean pathway. However this theory has to be verified with further studies using tracer techniques.

Table 7. Comparison of the discharge of Sipahidhara spring (SD) and that of all springs that were measured during the period 1947 to 1952 and 1995. (The discharge of Sariyatal spring is not included in the total discharge. Values given are in thousands of cubic meters.)

Year	1947		1948		1949		1950		1951		1952		1995	
Month	SD	Total	SD	Total	SD	Total	SD	Total	SD	Total	SD	Total	SD	Total
Jan	94	169	88	165	135	260	88	171	87	178	87	178	14	
Feb.	79	143	79	148	109	199	80	156	79	156	79	156	11	
Mar.	91	163	89	169	108	195	90	171	89	172	89	172	1	
Apr.	87	156	84	159	83	160	80	157	81	152	81	152	0.60	
May.	91	163	75	150	75	138	75	146	33	89	33	87	-	
Jun.	95	169	63	125	73	142	71	140	31	82	30	82	-	
Jul.	98	181	70	154	300	539	-	36	302	424	109	223	-	
Aug.	94	178	301	554	301	549	401	709	401	583	201	361	40	
Sep.	94	171	315	588	389	671	291	535	290	530	146	316	50	
Oct.	95	172	302	570	241	446	235	443	235	461	139	293	28	
Nov.	88	162	246	425	166	327	164	328	164	324	124	253	19	
Dec.	91	166	172	309	152	256	156	263	155	260	116	233	18	

4.0 ESTIMATION OF SEDIMENTATION RATE

The evaluation of sediment accumulation rate has been attempted by both modern radiometric dating techniques of sediments and also by conventional sediment balance method.

4.1 Radiometric Methods

Radiometric dating techniques have been proved as reliable tools for estimation of lake sedimentation rate and are being used the world over. Although several radioisotopes are useful in geochronological studies of lake sediments, ^{210}Pb and ^{137}Cs find wider application. ^{210}Pb dating technique was initiated by Goldberg (1963) and the technique was established for dating of lake sediments by Krishnaswamy et al. (1971). Since then numerous studies on the use of ^{210}Pb and ^{137}Cs both in the research and application fronts of lake sediment dating have been reported (Robbins and Edgington, 1975; Krishnaswamy and Lal, 1978; Ritchie and McHenry, 1985; Walling and He, 1993).

In order to estimate the sedimentation rate in Lake Nainital using radiometric sediment dating techniques, sediment cores were collected from different parts of the lake with a gravity corer. The length of collected cores ranged from 42 to 57 cm. Of these cores, three cores (Fig. 1) viz. Q, S & V which were considered to be representative of lake's sedimentary environment were subjected to radiometric dating. The cores were sliced into 2 cm sections and analysed at Bhabha Atomic Research Centre, Mumbai, India, for ^{210}Pb and ^{137}Cs activities. The profiles of ^{210}Pb and ^{137}Cs activities in different sediment cores with respect to depth are shown in Figure 12. The standard counting error in case of ^{210}Pb method was generally less than 10% in the upper sections of the cores and slightly higher at the deeper sections. In case of ^{137}Cs, the standard counting error was less than 10% in the core sections.

At the sampling location 'Q', the ^{137}Cs profile closely paralleled its weapon fall-out record pattern reported by earlier investigators (McHenry et al., 1973; Livingston and Cambray, 1978) i.e., an initial appearance in 1952-53; a subsidiary peak in 1957-58; and a major peak in 1963-64. With the depth corresponding to 1963-64 as time marker, the average sedimentation rate of Lake Nainital was computed and is listed in Table- 8.

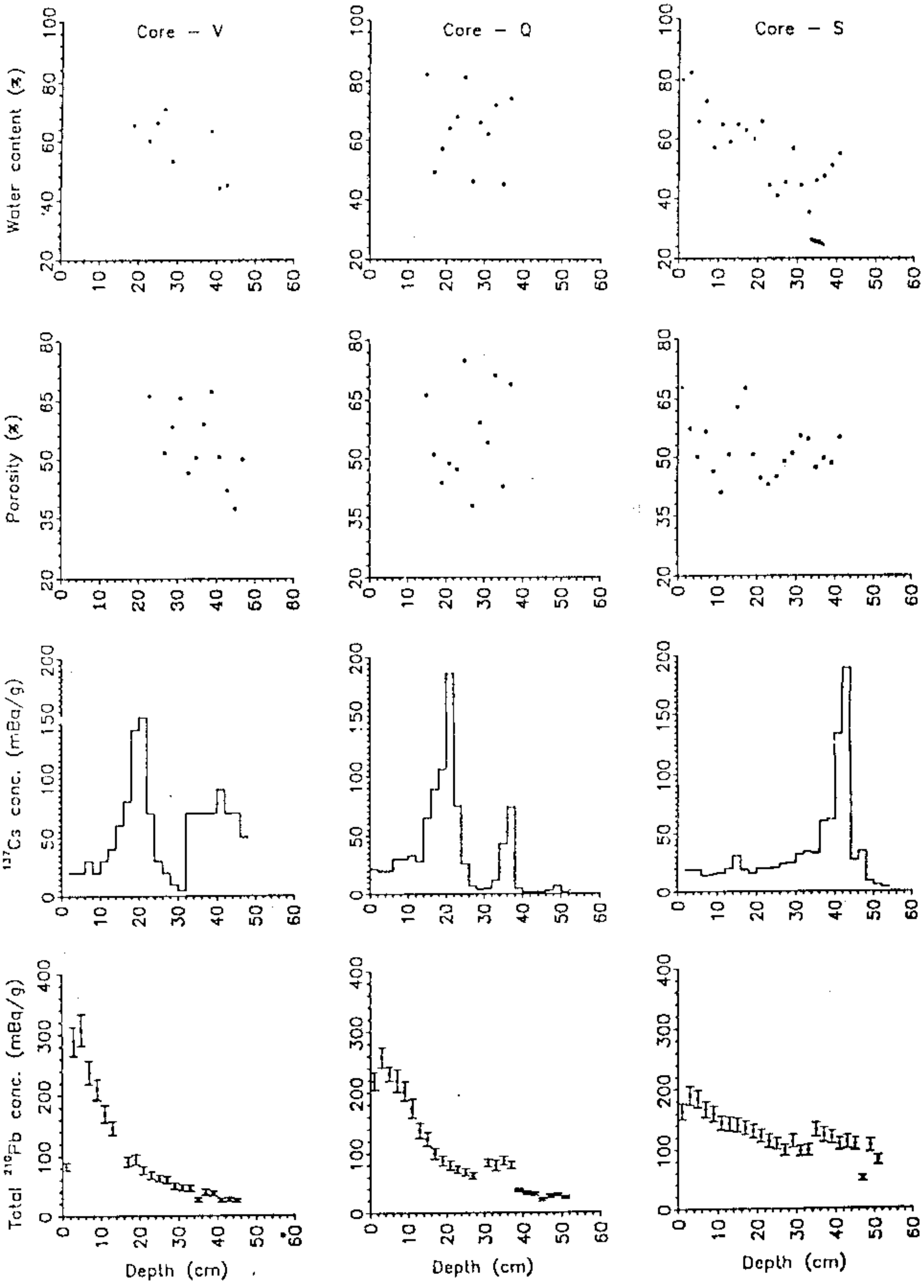


Fig. 4. ^{210}Pb and ^{137}Cs activity profiles in three core samples along with moisture content and density.

Table- 8: Sedimentation rates estimated by ^{210}Pb and ^{137}Cs in lake Nainital.

Sample Code	^{210}Pb Method (cm/yr)	^{137}Cs Method (cm/yr)
V	0.48 ± 0.04	0.60 ± 0.07
Q	0.64 ± 0.18	0.70 ± 0.03
S	1.24 ± 0.44	1.35 ± 0.05
D †	1.15 ± 0.09	-
Average	0.75	0.86

† Reported by Das et al. (1994)

The close similarity in the deposition and fall-out pattern of ^{137}Cs probably indicates that the residence time of ^{137}Cs in the lake water is small and post-depositional mobility of the radionuclide in the sediment core, if any, is insignificant. However, the ^{137}Cs profile of Lake Nainital may be viewed as an ideal case. Due to short length of the core obtained, the initiation and subsidiary peaks of 1952-53 and 1957-58 are not clearly seen in core samples 'V' and 'S' respectively (Fig.- 12).

As the atmospheric deposition flux of ^{210}Pb at the lake site is unknown, the available mean atmospheric flux of ^{210}Pb at Mumbai station, India, (0.025 Bq/cm^2/yr; Joshi et al., 1969) and the inventory supported by this flux, was assumed to be similar to the Nainital area (the annual rainfall at Nainital and Mumbai are comparable). As seen in Fig.- 12, at location 'V', the (total) ^{210}Pb profile shows a more or less an exponential decrease in concentration with depth to a constant value maintained by in-situ decay of ^{226}Ra. At other locations, the (total) ^{210}Pb concentration profile is not an exponential type (i.e., non-monotonic). Companion measurements of ^{137}Cs indicated that the top portions of the sediment deposit were not lost during coring.

4.2 Sediment Balance Method

Sediment inflow to the lake has been monitored at the two major inflow points to the lake. The variation of Suspended Sediment (SS) concentration in the inflow with time is shown in Fig.- 13. It has been observed that the average SS concentration during normal days is about 0.41 g/L and during rainy days is about 1.25 g/L. This information coupled with daily surface inflow gives the total suspended sediment input to the lake. The sediment outflow from the lake has been computed using the discharge from the lake through the sluices and the average SS concentration in the epilimnion (0.55 g/L). The rate of sediment accumulation in the lake, thus calculated is 0.69 cm/yr. The detailed sediment balance has been presented in Table- 9.

Table- 9: Rate of sediment accumulation estimated by Sediment Balance Method

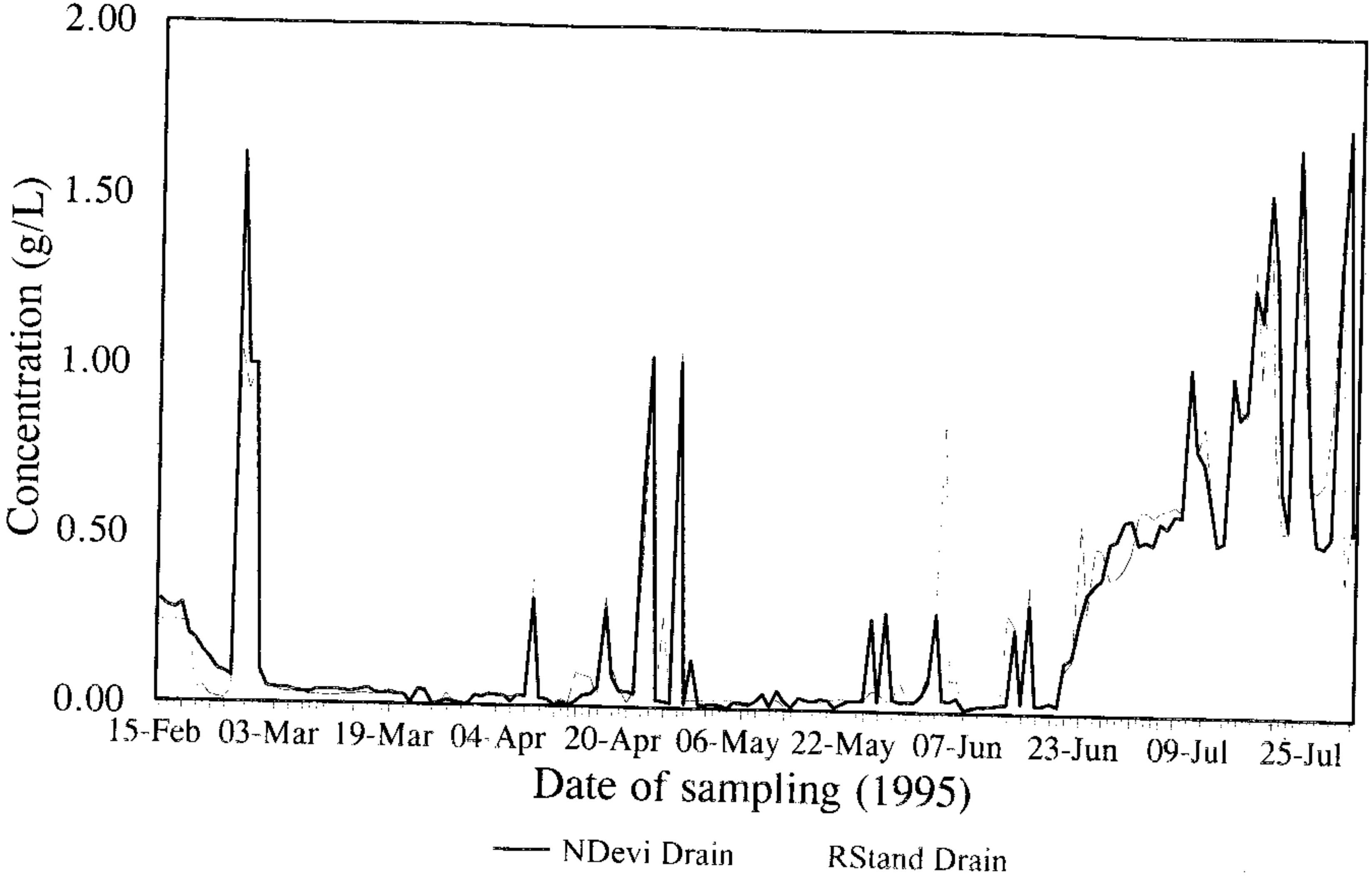
	Suspended Sediment Concentration	Total Susp. Sediment load (M^3)
Inflow through drains and during light rains	0.41 g/L	1500
Inflow during heavy rains	1.25 g/L	5097
Outflow through sluices	0.55 g/L	3422
Inflow - Outflow (sediment accumulation rate)		3175 (0.69 cm/yr)

5.0 EFFECT OF SEDIMENTATION ON WATER BALANCE

The sedimentation rates in different parts of the lake Nainital have been estimated using Cesium-137 (^{137}Cs) and Lead-210 (^{210}Pb) dating of sediment cores (Saravanakumar *et al.*, 1997). The sedimentation rate obtained by ^{210}Pb varies from 0.48 cm/yr to 1.24 cm/yr while in case of ^{137}Cs, it varies between 0.60 cm/yr and 1.35 cm/yr in different parts of the lake. The sedimentation rate is higher (1.15 cm/yr and 1.24 cm/yr) in the intermediate portions located just adjacent to the bank zones while comparatively moderate (0.64 cm/yr) in steeper bank zones. The deeper portions receive sediment at lower rate (0.48 cm/yr).

The total sedimentation in Lake Nainital, taking into account the mean accumulation rates, is 3462 m^3/yr (^{210}Pb) and 3901 m^3/yr (^{137}Cs). If the sediment deposition continues at the same rate, the lake may completely be filled up in 2160±80 years (^{137}Cs) or 2480±310 years (^{210}Pb) under normal environmental conditions. Considering the error limits of the life estimated by both the methods, the lake will be filled in 2200 years.

Fig. 13. Variation of suspended sediment inflow to Lake Nainital



As complete long term information on different water balance components is not available in case of lake Nainital, the relation of surface outflow from the lake with respect to the rainfall in the lake catchment in the past 100 years has been used to assess the effect of sedimentation on water balance of the lake. The plot of surface outflow versus rainfall is shown in Fig.- 14. To assess the effect of development of the town since early 1970s, the period 1901 - 1970 has been considered as one group and 1971 - 95 as the second group. There is a noticeable decrease in the surface outflow for the given rainfall in the latter period. This decrease is due mainly to the increase in pumping from lake.

Based on the estimated rate of sedimentation, there must have been an increase of 320000 m^3 in the overall annual outflow from the lake. If all other outflow components of the lake water balance equation such as evaporation, abstraction etc., remained within reasonable limits, the increase would then be noticeable in the surface outflow of the lake. But since the abstraction from the lake through pumping has increased manifold (as a consequence of increase in demand) such increase in S_0 is not noticed. On the contrary there is significant decrease in the surface outflow from the lake as seen from figure 14.

6.0 RESULTS AND DISCUSSION

A cursory glance of the Tables- 10a and 10b giving the values of the monthly water balance component of the lake indicates that the subsurface inflow is the major component. The net gain to the lake due to subsurface inflow accounts for nearly 39% of the annual inflow to the lake and the surface inflow accounts only for about 30%. The remaining is accounted by direct precipitation over lake surface (16%) and by inflow through the perennial drains(15%). Since the catchment rock formation is highly fractured with presence of several structural faults, one may expect significant groundwater inflow to the lake. The hydrologic residence time of the lake is about 1.72 years, considering in terms of depth the volume of lake (18.52 m) and outflow from the lake (10.76 m).

Fig.14. Annual rainfall - surface outflow relationship for Lake Nainital, worked out using long-term hydrological data. (Lower slope during 1971-95 due to increased pumping from lake)

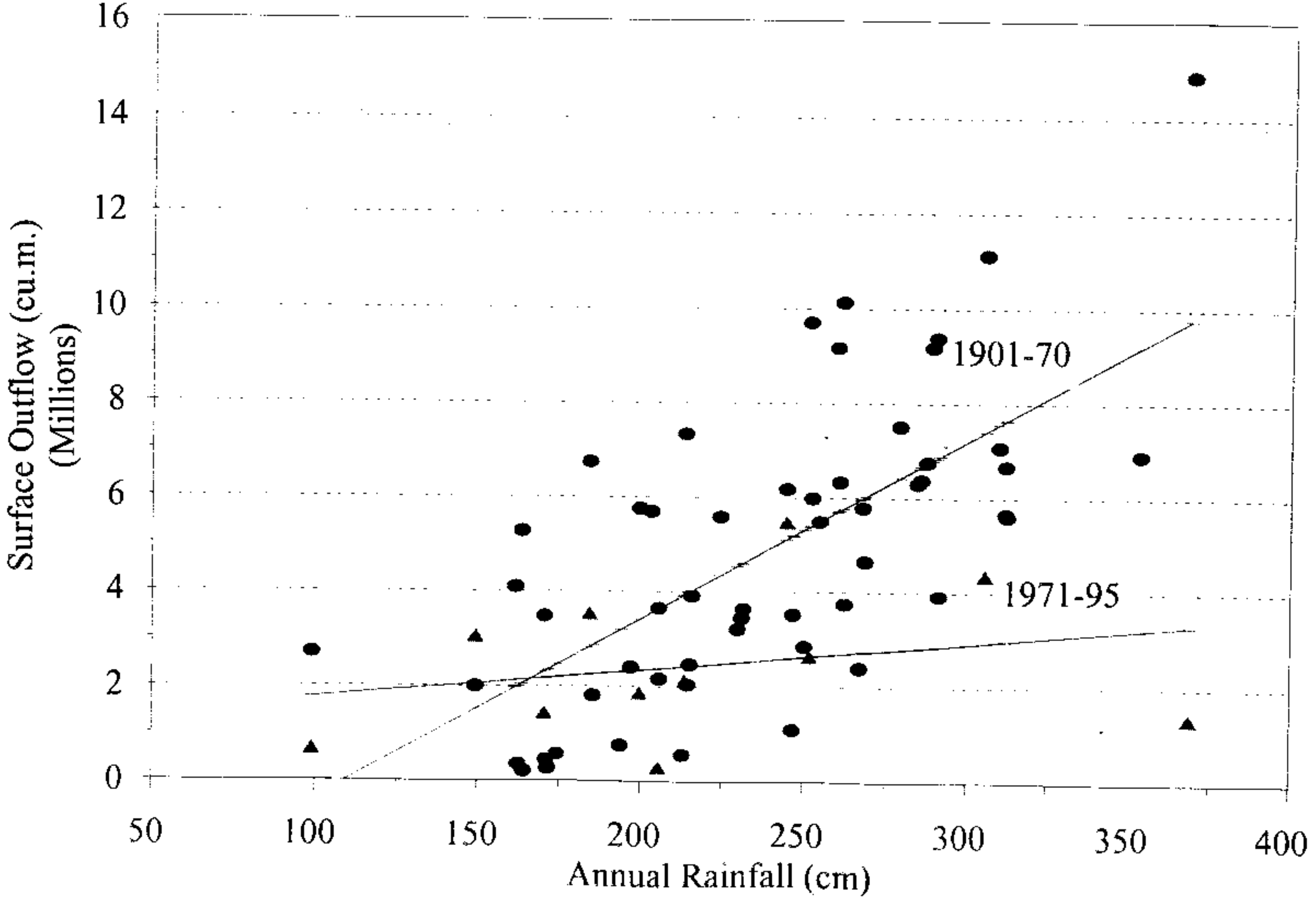


Table- 10a: Values of the water balance components of lake Nainital for the year 1994.

1994	L-Level	Pptn	ΔV	P_i	D_i	S_i	SS_i	S_o	E_o	Wo	SS_o
	M*	mm	x10^3 M^3	x10^3 M^3	x10^3 M^3	x10^3 M^3	x10^3 M^3	x10^3 M^3	x10^3 M^3	x10^3 M^3	x10^3 M^3
Jan	3.008	62	-8	29	54	0	34	0	30	61	34
Feb	2.948	15	-53	7	53	0	19	0	28	61	43
Mar	2.798	0	-92	0	48	0	30	0	50	74	46
Apr	2.598	62	-94	28	41	0	15	0	64	67	47
May	2.334	28	-126	13	40	0	38	0	73	92	52
Jun	2.092	242	2	109	40	56	1	0	62	94	48
Jul	2.529	491	191	223	75	417	343	427	54	322	64
Aug	2.873	432	192	197	121	354	467	569	47	214	117
Sep	3.141	43	66	20	104	0	598	389	51	89	127
Oct	3.139	5	-60	2	75	0	288	185	47	128	65
Nov	2.963	4	-80	2	62	0	93	0	29	134	74
Dec	2.781	2	-91	1	59	0	80	0	29	136	66
Net(M^3)		1386	-153	631	772	827	2006	1570	564	1472	783
Net(M)			-0.33	1.36	1.67	1.78	4.33	3.39	1.22	3.18	1.69
% to total Inflow / Outflow				14.88	18.27	19.47	47.37	35.76	12.87	33.54	17.83

* Lake level in UPPWD Gauge, Zero of the gauge is 1933.81 M above msl

Table- 10b: Values of the water balance components of lake Nainital for the year 1995.

1995	L-Level	Pptn	ΔV *	P_i	D_i	S_i	SS_i	S_o	E_o	Wo	SS_o
	M*	mm	x10^3 M^3	x10^3 M^3	x10^3 M^3	x10^3 M^3	x10^3 M^3	x10^3 M^3	x10^3 M^3	x10^3 M^3	x10^3 M^3
Jan	2.677	46	-73	21	54	0	11	0	32	93	34
Feb	2.512	59	-46	27	53	0	43	0	37	89	43
Mar	2.430	62	62	28	48	0	190	0	56	102	46
Apr	2.552	6	-95*	3	41	0	42	0	62	72	47
May	2.335	19	-156	8	40	0	20	0	72	100	52
Jun	1.975	89	-110	40	40	0	10	0	57	94	48
Jul	1.743	509	363	228	75	458	114	40	55	353	64
Aug	2.561	632	209	289	121	610	389	775	51	257	117
Sep	3.049	341	231	157	104	423	816	998	47	97	127
Oct	3.530	0	-64	0	75	0	277	212	45	94	65
Nov	3.375	0	-129	0	62	0	36	0	35	118	74
Dec	3.100	10	-142	5	59	0	19	0	26	133	66
Net(M^3)		1773	50	805	772	1491	1967	2025	575	1602	783
Net(M)			0.11	1.74	1.67	3.22	4.27	4.37	1.24	3.46	1.69
% to total Inflow / Outflow				15.99	15.35	29.60	39.06	40.61	11.52	32.16	15.71

* Lake level in UPPWD Gauge, Zero of the gauge is 1933.81 M above msl

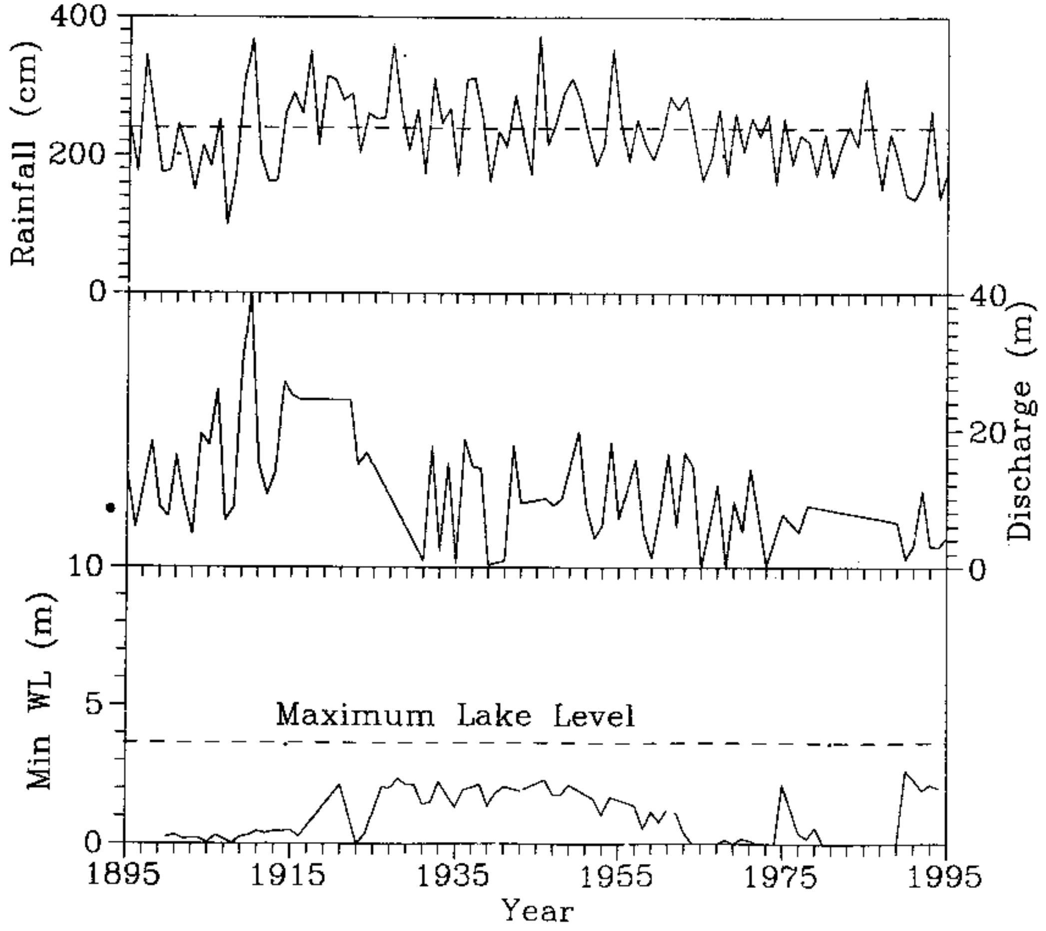
The variation in the subsurface inflow (Fig.- 11) to the lake is also corresponding to the nature of precipitation. The significant inflows during the months of February, March & April is influenced by the heavy snowfall and rainfall during late winter. The subsurface inflow declines during May and June and again shows an increasing trend upto September and then declines, also probably in line with the precipitation with a lag period of approximately one month. It is also notable that in spite of zero rainfall in the month of October the lake level continues to rise, which is mainly due to the subsurface inflow. This phenomenon has been observed for the period (from 1895 to 1995) for which lake level and rainfall records are available. The annual rainfall in the catchment, the minimum water level recorded in the lake and the quantity of water drained through the sluice gates for the past 100 years are shown in Figure 15. It is observed that even during the years of below normal rainfall, there is no water shortage, and that a substantiative quantity of water had to be drained through the sluice gates.

Tables- 10a and 10b also reveals that one of the major outflow from the lake is pumping (32%), while 41% of annual outflow is accounted by discharge through the sluices, which are operated only during rainy season. Free water eveporation accounts for about 12%. Remaining 15% water is attributed to the subsurface outflow as springs.

7.0 CONCLUSIONS

Water balance of Lake Nainital has been computed for the first time. The values of different components have been calculated adopting either direct field observations or established estimation methods. The study reveals that there is significant subsurface inflow to the lake. Since the lake is bifurcated by a fault zone (Naini Fault or Lake Fault), the inflow could be through this and other associated faults and fractures. Further, the dolerite dyke present at the SW side of the lake catchment probably acts as a barrier of southward groundwater flow and diverts the flow towards the lake. Pumping of lake water for the city water supply accounts for the maximum withdrawal. Therefore the pumping strategy adopted will have a direct bearing on the water availability during different seasons. The discharge through the sluices during the rainy season accounts for nearly one third of the current outflow. This implies that even for a hydrological year of below normal rainfall, there would not be any scarcity of water, provided the present withdrawal trend is not disturbed.

Fig. 15. **Annual** rainfall, Surface outflow and Minimum lake level of Lake Nainital from historic data



The sedimentation rate, estimated by both radiometric dating techniques of the lake sediment cores and by sediment balance method compare well with each other. The average sedimentation rate in the lake is around 0.69 cm/yr. This rate is not too high to threaten the lake's existence as the useful life of the lake, computed using the average rate of sedimentation is around 2200 years. However, the sedimentation plays a major role in the hydrological characteristics of the lake. The negative effects which have resulted due to sediment accumulation are a) reduction in the capacity of the lake which is, however, not significant and b) reduction in the discharges of the downstream springs, around which certain communities or dwellings have developed over the years.

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DIRECTOR

Dr. S. M. SETH

CONTRIBUTORS

Dr. BHISHM KUMAR
Scientist 'E'

Mr. Rm. P. NACHIAPPAN
Principal Research Assistant

SPECIAL ASSISTANCE BY PROJECT STAFF

Dr. S. P. RAI
Project Officer

Mr. VINOD KUMAR
Technical Assistant

Mr. B. C. DUNGARAKOTI
Junior Technical Assistant